Hybrid Electric Vehicle Testing
Final Report
– Volume 1 of 8 –

Saturn Hybrid Electric Vehicle Research Program
University of Maryland at College Park

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ABSTRACT

(Read this if you want a brief overview of the research –a more technical version labeled Executive Summary follows)

The University of Maryland converted a 1991 Saturn SL2 to a parallel drive hybrid electric vehicle. This vehicle was entered into the Department of Energy's (DOE) 1994 Hybrid Vehicle Challenge and won first place in its class. Subsequently, further research was conducted into optimizing its performance through funding by the National Renewable Energy Laboratory (NREL). The contract called for us to provide efficiency maps of the individual components and to attempt to optimize the control strategies for maximum fuel efficiency. This report describes the results of that research.

The drivetrain consists of a 1.0L Suzuki three cylinder engine that was extensively modified to run on either a mixture of 85% methanol and 15% gasoline (M85) or 85% ethanol and 15% gasoline (E85). The engine was coupled to a Subaru Electronic Continuously Variable Transmission (ECVT), which was conventionally connected to the front wheels. In between the transmission and the engine was an overriding clutch coupling that connected a Unique Mobility DR 156s DC brushless electric motor to the powertrain. Energy to drive the electric motor and to receive regenerative energy when appropriate, from the internal combustion engine or from regenerative braking, was provided by a Saft STH NiCd battery pack with a nominal voltage of 155 V and a 21 Ahr (C_5) rating, resulting in an energy capacity of 3.3 kWhr. Control of the system was performed using an Allen-Bradley SLC 5/03 controller, and total vehicle operation was essentially "drive by wire". This vehicle can be considered to be a "power assist" parallel drive hybrid.

Efficiency maps were generated for the Suzuki engine, the Subaru ECVT, the Unique Mobility electric motor, and for the polychain belt coupling the electric motor to the transmission. Charge/discharge characteristic maps for the batteries were generated prior to the start of this program. The control program uses this information and attempts to operate the vehicle in a way that will maximize the overall system efficiency. The basic control strategy "load levels" the engine: i.e., at loads normally considered to be low for a conventional vehicle such as low speed cruise and idle, the engine powers the vehicle and simultaneously charges the batteries via the electric motor/generator. At medium power demands, the vehicle may operate on just the engine alone. At peak power demands, the vehicle receives its power from both the engine and the electric motor. In all braking modes, regenerative braking is used to recharge the batteries.

On the FTP-75 driving schedule, the vehicle achieved 43 mpg gasoline equivalent (with a 4% decrease in the state of charge of the batteries) and on the HWFET, a 75 mpg equivalent (with a 0% change in the state of charge of the batteries). This amounts to a 65% improvement in the vehicle's baseline fuel economy in the FTP cycle and an 83% improvement in the highway cycle using the unadjusted data from EPA's 1992 database (the first year EPA had data for the Saturn). However, while CO emissions were below the most stringent 1997 California ULEV emissions, the HC emissions were at the Federal tier 1994 levels and the NO_x emissions were at the 1975 Federal levels.

EXECUTIVE SUMMARY

(For the reader seeking more specific technical information and details in summary form)

The University of Maryland converted a 1991 Saturn SL2 to a parallel drive hybrid electric vehicle. This vehicle was entered into the Department of Energy's (DOE) 1994 Hybrid Vehicle Challenge and won first place in its class. Subsequently, further research was conducted into optimizing its performance through funding by the National Renewable Energy Laboratory (NREL). The contract called for us to provide efficiency maps of the individual components and to attempt to optimize the control strategies for maximum fuel efficiency. This report describes the results of that research.

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<u>EFFICIENCY RESULTS</u>

Subaru Electronic Continuously Variable Transmission (ECVT)

The efficiency of this transmission ranged from 75% to near 95% depending on the throughput torque, vehicle speed, and the input rpm of the transmission where shifting was set to occur (input shifting speed). It was highest at a vehicle speed of 60 kph with an input shifting speed of 2000 RPM, and lowest at combinations of low and high vehicle speed along with an input shifting speed of 3000 RPM. These relationships can be found in the body of the report in Figures 11-13 on pages 35 and 36. In general, greater throughput torque yielded the highest efficiencies. This last result is to be expected since the internal losses (such as hydraulic pump, bearing, and fluid turbulence) tend to remain relatively constant over a wide range of operating conditions.

Suzuki 1.0L Three Cylinder M85/E85 Engine

The internal combustion engine used in this project started out as a production Suzuki 1.0L three cylinder out of a Geo Metro, which used gasoline throttle body fuel injection. It was extensively modified by raising the static compression ratio to 12.5:1 via custom aluminum pistons and machining of the cylinder head, by employing tuned tubular intake and exhaust manifolds to optimize its efficiency between 3000 and 3500 RPM (this was the range where the engine produced the greatest torque), and by installing and programming a sequential multi-port fuel injection system. At various stages of the program the engine ran on M85 (early) and then E85 (late). Engine calibrations for M85 were determined by cradled engine dynamometer testing where both the fuel injection and ignition timing were varied. To convert the engine fuel injection programming to operate on E85, the fuel injection pulsewidths were adjusted for the different fuel energy content levels. Ignition timing values for E85 remained identical to the M85 calibrations, and the fuel injection values were verified through road testing and data collection. A maximum efficiency of slightly over 31% (power in / power out) was reached at wide-open throttle at 3500 RPM while testing with M85 on the engine dynamometer. At this point the engine was producing 60.7 ft-lb (82 N-m) of torque and 40.7 bhp (30.4 kW). The lowest efficiencies were at low power output combined with high and low RPM.

Unique Mobility DR 156s DC Brushless Electric Motor with CR20-150 Controller

This electric motor/controller combination is capable of operation to 200V with a continuous rating of 21.2 bhp (15.8 kW) at 6750 RPM. In this project, with the lower in-vehicle nominal battery bus voltage of 155 volts, the combined rating was 17.5 bhp (13.0 kW). Measured maximum efficiency of the combined electric motor and controller was 87% at 6000 RPM, an output torque of 10 ft-lb (13.5 N-m), and an input load voltage of 127 V. Slightly higher efficiencies are possible (low 90%) with increased bus voltage and torque output.

Gates Polychain Belt

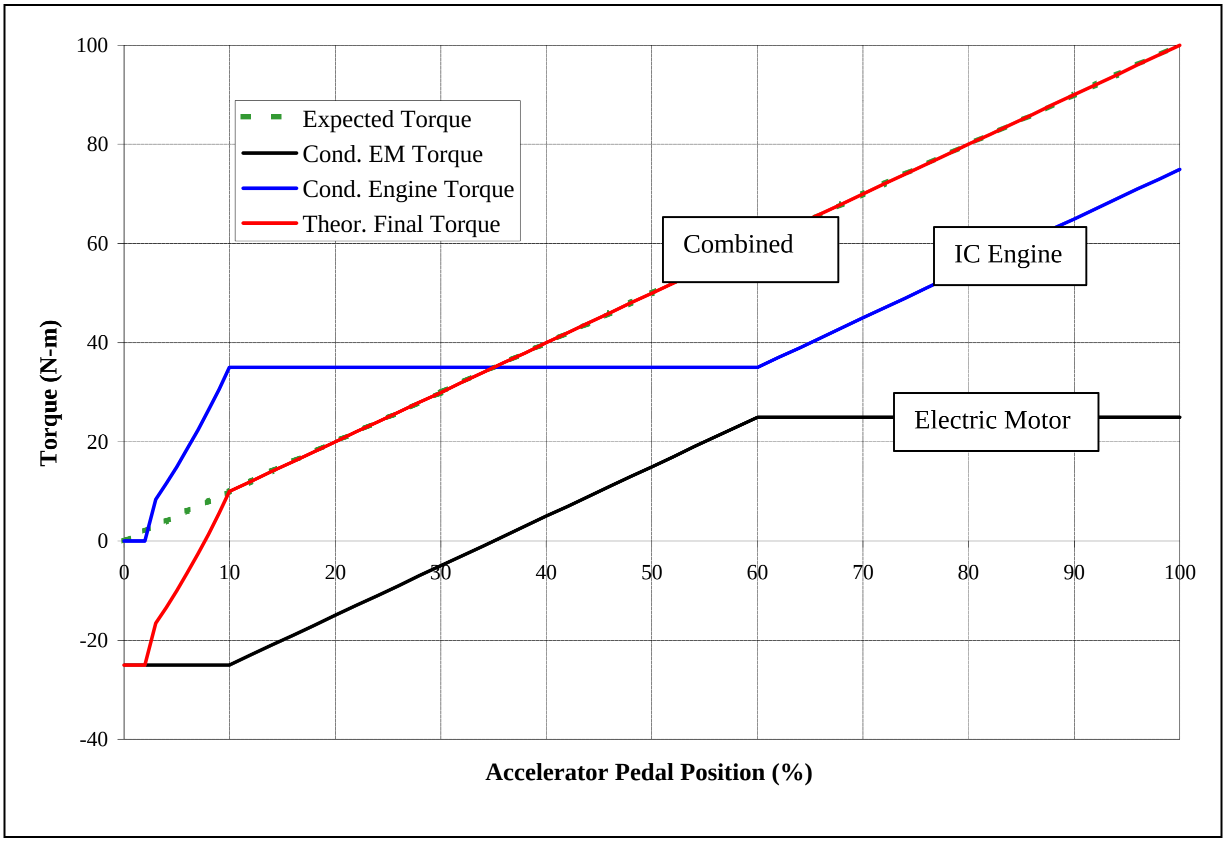
The Unique Mobility electric motor/generator was coupled to the Subaru ECVT input shaft through a Gates Polychain belt and a Dana AL 20 overrunning clutch assembly. Using the overrunning clutch, the transmission input could consist of a combination of the engine and the electric motor/generator, or the electric motor/generator alone. The clutch assembly worked in the following way: the flanged overrunning outer race of the clutch was bolted directly to the transmission input as well as to one of the polychain pulleys, i.e. the electric motor/generator, while the inner race connected to the engine flywheel via a keyed shaft damped by a torsional coupling. This enables electric motor/generator operation of the transmission independent of the engine. However, if the engine's clutch race RPM was driven to match that of the electric motor/generator's clutch race RPM, then the clutch would mechanically lock and allow the engine to drive both the transmission and the electric motor/generator. Likewise, if the RPM of the electric motor/generator was greater than that of the engine, then it alone powered the transmission. Consequently, during regenerative braking when the engine RPM was low, power would flow back through the electric motor/generator to charge the batteries.

The efficiency of the belt drive depends on the initial tension set on the belt, and the torque transmitted by the belt. The greatest efficiencies were obtained at a pretension of the belt set to just prevent it from jumping teeth when transmitting the maximum amount of torque from the electric motor. This efficiency was on the order of 92%. Belt speed seemed to have relatively little effect on the belt efficiency over the operating speeds of the electric motor.

VEHICLE SYSTEM CONTROL

The vehicle system was controlled using an Allen-Bradley SLC 5/03 Programmable Logic Controller (PLC). Thirty-two input signals were monitored, and there was capability to send twenty-eight signal outputs. The braking system remained stock, but the accelerator pedal was connected only to potentiometer whose signal was monitored by the PLC. Depending upon the speed of the vehicle, the battery state of charge, and the accelerator position, the PLC would send a command signal to a stepper motor operating the engine throttle and a corresponding command signal to the electric motor controller. This configuration is sometimes called "drive by wire".

Having obtained the efficiency maps of the various components, it was then determined through a basic steady-state simulation of a parallel hybrid when and where to utilize the engine, the electric motor, or a combination of both, to yield the best possible system efficiency. The basic strategy was to maintain constant engine load at an efficient and battery charge sustaining torque level, while compensating for the driver's total powertrain torque request (accelerator position) with the electric motor. This strategy is further described in the body of the report, and illustrated in Figure 10 on page 32. For the sake of clarity this Figure is reproduced below.



The vertical axis in this Figure is torque output (negative values are torque input, i.e. the electric motor is being operated as generator), and the horizontal axis is accelerator position. Between 0-3% accelerator position, the driver is requesting no IC engine torque but full electric motor generator capability. This operating point is intended to simulate conventional vehicle engine braking under deceleration conditions, and has no major negative consequences during acceleration. Between 3 and 8% position all available IC engine torque is directed to the generator. Beyond 8% position the vehicle will begin to move, with the IC engine accelerating the vehicle and also inputting power to the generator. A first time driver in this vehicle might be expecting the dashed line response as the accelerator is depressed. The effect of this particular control strategy is simply that the accelerator needs to pressed further down before the vehicle will move, and takes only a few moments to become familiar with.

At the 10% position, the 35 N-m programmed IC engine torque is developed, and the generator demands begin to linearly decrease. At the 35% position, the generator demands are 0. Between 35% and 60% position, the electric motor now begins to assist the IC engine in propelling the vehicle. From 10 to 60% position the IC engine torque remains constant at 35 N-m. Beyond the 60% position, the electric motor has reached its maximum value of 25 N-m, and thus the IC engine is required to increase its torque output. The curve labeled “combined” is what the driver and vehicle experience as the accelerator is depressed.

The speed of the vehicle and the state of charge (SOC) of the batteries alters the desired constant engine load, and thus the control signal to the engine’s throttle-controlling stepper motor. A brief summary of these control strategies follows, and a more complete description can be found in the body of the report on page 31.

Engine torque was maintained relatively constant first by the constant RPM shifting of ECVT, and second by using the efficiency testing data to determine required engine throttle positions for desired torque output levels. The SOC was monitored by first measuring the battery voltage and current at one second intervals, and then computing a Whr change during this time. This Whr change was adjusted for battery voltage inefficiency by using experimentally derived, nominal voltage, lookup tables stored in the PLC's program. After the Whr number was adjusted, the accumulated energy was then calculated to include the latest interval and a new SOC was determined. Typically, higher vehicle speeds or low battery SOC would increase the constant engine load to maintain or increase battery SOC. The baseline constant engine torque value was determined to be 35 N-m for the vehicle to be charge sustaining over two UDDS driving cycles.

EMISSION CONTROL

The engine's emission control system employed a closed loop oxygen sensor and a three way, electrically heated catalyst manufactured by Emitec. In addition, there was a Schatz heat battery (no phase change material in this model), and an electric pump which injected air into the exhaust manifold during engine warm-up. This is a common practice for attempting to minimize the unburned hydrocarbon emissions associated with the slightly rich mixtures necessary during cold starts. As will be shown in the next section, the CO and HC emissions were at acceptable levels, but NOx was not.

FUEL ECONOMY AND EMISSIONS TESTING RESULTS

The completed vehicle was tested at Environmental Research and Development (ERD), an EPA certified laboratory. Eleven tests were conducted consisting of UDDS, FTP-75, and HWFET driving cycles. On the FTP-75 driving schedule, the vehicle achieved 43 mpg gasoline equivalent (with a 4% decrease in the state of charge of the batteries) and on the HWFET, a 75 mpg equivalent (with a 0% change in the state of charge of the batteries). This amounts to a 65% improvement in the vehicle's baseline fuel economy in the FTP cycle and an 83% improvement in the highway cycle using the unadjusted data from EPA's 1992 database. However, while CO emissions were below the most stringent 1997 California ULEV emissions, the HC emissions were at the Federal tier 1994 levels and the NO_x emissions were at the 1975 Federal levels.

INTRODUCTION

The University of Maryland has been involved with most of DOE's vehicle student competitions aimed at improving fuel economy and adapting vehicles to run on alternative fuels. Beginning in 1988, we converted a Chevrolet Corsica to run on M85. This was followed by the Natural Gas Vehicle Challenge, where students converted a GM pickup to run on natural gas. In 1994, we converted a 1991 Saturn SL2 sedan to a parallel drive hybrid electric vehicle, which won its class at the competition. Based on this success, we submitted a proposal to NREL to further develop this vehicle and to provide efficiency maps of the major components within the vehicle. The contract was awarded, and we began work in 1995 in earnest. The testing results and data are voluminous, and we have submitted to NREL electronically the raw data as well as the analysis of this data, and have provided hard copies of these results in eight volumes.

Volume 1: Final Report
Volume 2: PLC Program Code
Volume 3: PLC Programming References
Volume 4: ECVT Transmission Testing
Volume 5: M85 Engine Testing
Volume 6: Electric Motor and Belt Testing
Volume 7: Vehicle Fuel Economy Testing
Volume 8: Background Documents

This report (Volume 1) describes the results of those efforts, and summarizes the key findings. A description of the electronically sent data and file structure may be found in the Appendix of this report.

EXPERIMENTAL PROCEDURE

Eddy Current Engine Dynamometer

All individual component efficiency testing, i.e. transmission, engine, electric motor, and polychain belt, was performed using a Borghi & Saveri FA-50/30 SLV eddy current dynamometer. In this report, the eddy current dynamometer will be referred to as the “engine dynamometer” to differentiate it from a chassis dynamometer used to test a total vehicle drivetrain through the wheels. In contrast, this dynamometer has a single input shaft, to which one connects the testing device output, and a table fixture, to which one rigidly mounts the testing device.

This dynamometer is designed for torque or speed control and is nominally rated at 50 bhp (in actual use we have used it in tests of up to 80 bhp). For these tests, torque control was selected using a ten-revolution potentiometer for load adjustment. Input torque measurement was obtained using a load cell under compression or tension, depending upon the driving input’s rotation. The load cell was attached to the frame’s base and a moment arm from the rotational brake housing. Specifications for the Omega LCCA-100 load cell may be found in Volume 4 under Certification Documents. Calibration of the load cell was completed before every testing session, using the zero-point calibration technique described in the next section.

Daytronics DataPac Datalogger

Electronic datalogging for all individual component efficiency testing was collected with a Daytronics DataPac System 10KUD. The DataPac is configured as a modular data acquisition system, providing four card slots for a variety of input conditioning. For the component efficiency tests, the only card selection requirements were for analog voltage measurement and full-bridge strain gage measurement for the force measurements. With additional cards available, the DataPac can also be used to measure temperature using a thermocouple card, analog current, and a variety of typical engineering measurement devices. The DataPac is capable of scanning 160 channels at 2500 channels per second. Typically, one strain gage card with four input channels was used in conjunction with two analog voltage cards (four or eight channels each). Data recording at each steady-state operating point lasted for ten seconds providing 150 data points (15 per second).

Control of the DataPac features was enabled through a personal computer via RS-232-C full-duplex, serial communication using a variety of preset ASCII mnemonic commands. Accordingly, an executable program written in Basic was developed in previous experiments with the DataPac to perform configuration setting changes, input conditioning changes, and customization of the data collection (which inputs are recorded, what sequence the inputs are recorded, time of recording, etc.). Modification of the original Basic program was completed for each test to provide proper testing comments (i.e. sump oil temperature, exhaust temperature, current limiting light illumination, etc.).

Channel calibrations for each input were performed using the DataPac software during every test session, for strain gage measurement devices, or at the beginning of a component test setup, for analog voltage measurement devices. Zero-point calibrations were used to calibrate both device types. Selecting a zero-point calibration in the DataPac software requires the user to first establish the measurement device at its zero excitation. For a load cell, this means setting it at its no load condition. For a voltage source, grounding to its own common is sufficient. The second step in a zero point calibration is to establish a known excitation at the measurement source. For a load cell, the technique used was to simply hang a weight directly from the load cell, or from a moment arm at a known distance. Simply measuring a hanging weight from the load cell required post-conditioning of the data using the test fixture moment arm to give the actual test torque, whereas the second method of hanging a weight on a moment arm produced test torque directly in the data file. Typically, placing a 17.0 lb weight at the end of a removable and counter-balanced moment arm bolted to the dynamometer brake provided 51.0 ft-lb of torque (moment arm length = 3.0 ft) for which the DataPac was calibrated. For a voltage source, a voltage supply was connected in parallel to the DataPac and a high precision voltmeter. Once the calibrations for each test were completed satisfactorily, channel scaling and offset values (internal to the DataPac) were recorded for inclusion later into the testing data.

U of MD FutureCar Lab Power Chassis Dynamometer

This piece of equipment is a basic in-floor type chassis dynamometer with dual rollers and water brake absorption. It was manufactured by Clayton and has a capacity of 200 bhp. Torque was measured with a strain gage load cell. It is almost exclusively a steady state piece of equipment, and was used primarily for loading the drivetrain in a safe, controlled laboratory environment.

Environmental Research & Development Corporation

Environmental Research and Development (ERD) Corporation is an independent company located in the northern suburbs of Washington D.C. ERD's emissions testing facilities are certified by the EPA to perform a variety of automotive emission tests. The completed vehicle was tested in their facilities using UDDS, FTP-75, and HWFET driving cycles. All told, eleven tests were conducted.

ELECTRONIC CONTINUOUSLY VARIABLE TRANSMISSION (ECVT) EFFICIENCY TESTING

Rainer Vogel, a German exchange student, completed much of this work during the summer of 1995 as his Diploma Thesis entitled "Design and Construction of a Transmission Test Fixture for a Subaru ECVT". His complete report can be found in Volume 4. What follows is a brief summary of how the tests were conducted and their results.

In order to measure the efficiency of the transmission, it was necessary to build a fixture to provide input power to the transmission and to measure this input power. In addition, due to the torque and speed characteristics of our B&S eddy current engine dynamometer, it was necessary to build another fixture to increase the speed of the output shaft of the transmission before coupling it to the dynamometer.

Test Fixture Construction and Dynamometer Setup

A Saturn 1.9L gasoline engine was used to generate the input power to the transmission. Contract terms precluded us from purchasing an in-line torque cell to measure the input torque. Instead we built the engine-mounting fixture pictured in Figure 1. The Saturn engine was supported in a cradle that was free to rotate on bearing blocks about the center of the engine's crankshaft. The reaction torque preventing the entire cradle from rotating was determined by a fixed, strain gage type load cell mounted to the side of the cradle. The input power to the transmission was thus determined from this torque and the engine RPM. The rotational speed of the engine and dynamometer were measured by inductive sensors in close proximity to the 129 tooth flywheel of the Saturn and to a 60 tooth timing gear on the dynamometer. The stock electromagnetic powdered clutch that comes with the transmission was used to couple the engine and transmission together. This clutch contains driver and driven plates coupled together by a powered magnetic material that becomes solid in the presence of a magnetic field.

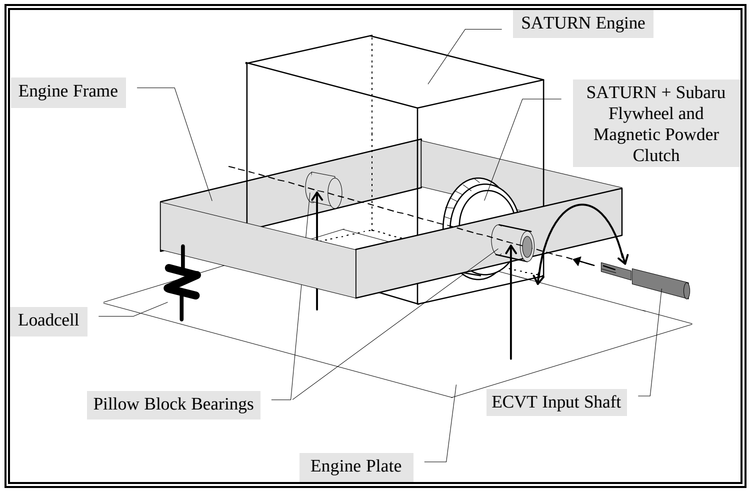


Figure 1. Transmission Testing Engine Support Construction

The transmission was a stock unit from a Subaru Justy. Output power was taken from one side of the differential, with the other side being pinned internally to its carrier. The power was transmitted to the speed increaser through a half shaft, and from the output of the speed increaser to the engine dynamometer through a flexible coupling. The speed increaser is shown in Figure 2 and Figure 3.

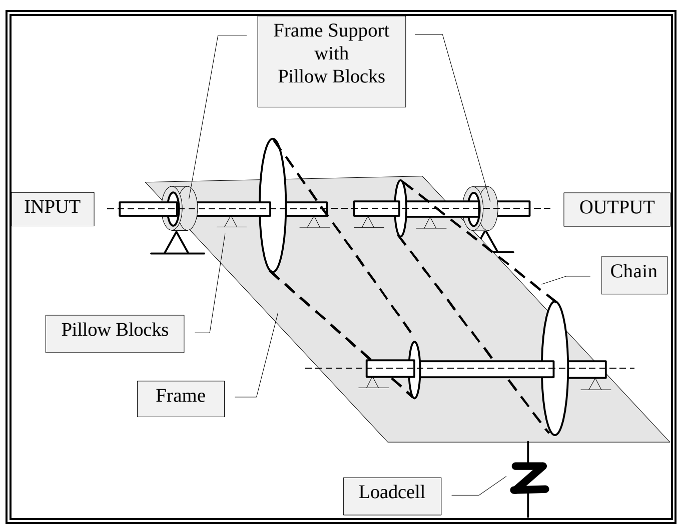


Figure 2. Chain Drive Speed Increaser Construction

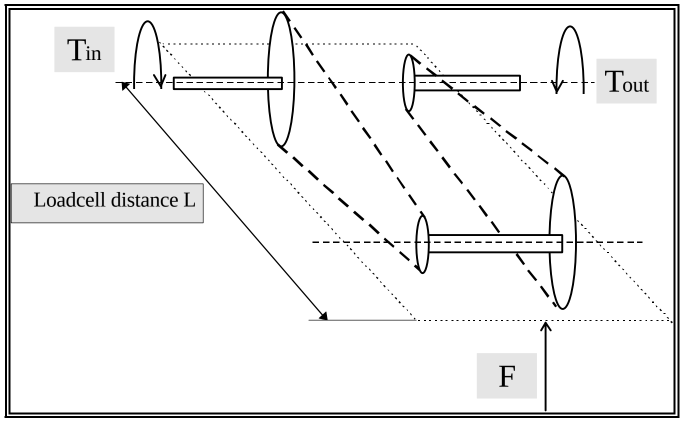


Figure 3. Speed Increaser Force Freebody Diagram

The output torque was measured with the engine dynamometer, and the input torque was then determined knowing the force F and the distance L. The key limits on the transmission and components were:

Maximum torque capability of the transmission: 70 ft-lb
Maximum torque capability of the electromagnetic clutch: 100 ft-lb
Maximum power capability of the transmission: 66 hp

Experimental Procedure and Data Collection

The following data acquisition preparations were performed each and every time a testing session began, and rechecked for changes if any testing sessions were stopped and restarted for any reason.

<u>Test Fixture Preparation Procedure</u>

1. Turn on data acquisition system to warm-up load cells approximately 15 minutes.
2. Remove the two load cells from the Saturn engine stand and chain gearbox.
3. Calibrate both load cells following the zero-point calibration procedure using a 74.6 lb weight. Reinstall the engine stand and gearbox load cells.
4. Once the load cells are reinstalled, zero the load cells by adjusting the offset in the calibration procedure of the data acquisition system until the cell output is zero on the DataPac readout.
5. Calibrate the dyno load cell using the zero-point calibration procedure and 17.0 lb weight at 3.0 feet.
6. Calibrate RPM voltage sensor channel for the engine RPM using the Fluke 88 multimeter for an accurate measurement of RPM and the zero and known point procedure.
7. Record all calibration data in data collection notebook.
8. Record the percent humidity, ambient temperature, and barometric pressure into the data collection notebook.
9. Follow all relevant pre-start procedures listed in the engine testing document posted on the viewing window, such as checking the water tower coolant level, engine oil, transmission fluid, fuel level, dyno water pressure, exhaust and cooling fans, oiling the gearbox chains, fixture alignment and support, etc.
10. Turn on the ventilation and cooling fans.
11. Start and warm-up the engine and transmission at an idle RPM with the electromagnetic clutch engaged (engine coolant temperature over 180°F, and transmission fluid temperature over 45°C).

Data Collection Procedure

1. Be sure to provide repeatability test data points at the start and end of each test session.
2. For all tests, RPM variations from the desired data point interval should deviate no more than ± 100 RPM. Attempt to keep engine torque variations less than ± 2 ft-lb from the desired data point interval.
3. Set the transmission's shift cam cable to achieve the desired engine shifting RPM for a series of tests. Engine shifting RPM intervals should be 500 RPM.
4. Increase engine throttle with low load from dyno until the transmission shifts into high (pulley ratio of 0.5:1). Do not exceed 6200 RPM on the dyno.
5. Holding engine throttle constant at the appropriate torque load interval (10 ft-lb increments), increase dyno load to decrease output dyno RPM in such that the pulley ratio is changing in increments of 0.5 (0.5, 1.0, 1.5, 2.0, and 2.5) and take data readings. Refer to reference dyno RPM on data sheets for the desired gearbox ratios. Engine torque should not exceed 70 ft-lb.
6. Activate the pressure solenoid at each data point for engine torque lower than 45 ft-lb after data has been taken with the pressure solenoid off. Assure that all data references are matched before taking the data, particularly dyno RPM since the pressure solenoid will increase efficiency, requiring more dyno load.
7. Change transmission throttle cable position to change engine speed for the next series of tests and repeat from step 4 until entire map is defined.

Table 1. Transmission Testing Data Collection Procedures

The dynamic signals from the three load cells, the two-RPM inductive pickups, and from three pressure transducers monitoring the internal pressures within the transmission were recorded using the Daytronic DataPac connected to a PC. The sample rate of these 8 channels was typically 15 times per second, and a test would last for 10 seconds, resulting in 150 scanned measurements. The data was then averaged to produce single values for each of the measured parameters for the given test conditions. Transmission fluid temperatures were measured just prior to starting data acquisition, and were entered into the file header.

The data from each test was then processed according to ANSI/ASME performance Test Code 19.1-1985, and the uncertainties at the 95% and 99% levels determined.

Efficiency Calculations

The efficiency of the transmission was determined from equation 1 which simply divides the output power by the input power. The output power incorporates the bearing losses of the speed increaser, designated as the gearbox torque. The output RPM is divided by 6 due to the speed increaser gearing.

$$h = \frac{(T_o + T_g) * (RPM_o / 6)}{(T_i * RPM_i)}$$

Equation 1. Transmission Efficiency Measurement Calculation

- T_o - Dynamometer torque (ft-lb)
- T_q - Gearbox torque (ft-lb)
- T_i - Engine torque (ft-lb)
- RPM_o - Dynamometer angular velocity (RPM)
- RPM_i - Engine angular velocity (RPM)
- η - Transmission efficiency (%)

METHANOL-FUELED, INTERNAL COMBUSTION ENGINE EFFICIENCY TESTING

Engine Modifications and Dynamometer Setup

The engine used in this research started out as a Suzuki 1.0L three cylinder, spark ignited engine incorporating throttle body fuel injection, the base engine from a pre-1995 Geo Metro. For this program, multi-port fuel injection was utilized by drilling out the injector bosses already cast in the cylinder head (for optional production turbocharged engines). Custom-alcohol-specific, pencil stream fuel injectors manufactured by Siemens were used with a constant pressure differential across the injector of 55 psi. To take advantage of the higher octane rating of both M85 and E85 fuels, the engine’s static compression ratio was raised to 12.5:1 by machining the cylinder head and using flat top, custom-made JE aluminum pistons with a gapless secondary compression ring. Cylinder head porting and valve seat deshrouding increased air flow through the engine, while custom intake and exhaust manifolds were designed and constructed to maximize volumetric efficiency at 3100 RPM. Typical “blueprint” engine building procedures were used during the assembly of the engine, ensuring correct tolerances and balancing.

The engine was coupled to the engine dynamometer using a heavy-duty universal joint type coupling. Engine RPM and torque data values were determined by using the inductive pickup and strain gage load cell as described in the transmission testing section.

Emtech E6s Engine Management and Calibration Techniques

The Emtech E6s engine management system is typical of third party engine computers available today. It is fully programmable via a PC (including changes made online), and manages fuel injection pulse width and spark timing. These parameters are modified by several input variables including engine RPM, manifold pressure, coolant temperature, air temperature, and oxygen sensor voltage. The following table illustrates the basic calibration procedure used to adjust the fuel injection and spark timing values for warmed up, steady state operation on the engine dynamometer.

1. Adjust fuel injection timing near current closed loop operation (± 5%).
2. Adjust ignition timing to maximize output torque at current operating point, usually steps of ± 2°, monitoring exhaust temperature just outside the cylinder head exhaust port, approximately 700° C desired for continuous operation.
3. Readjust fuel injection timing slightly rich of the closed loop operating point, usually set near – 2% to – 4% closed loop correction.
4. Examine exhaust gas emission levels, either pre-catalyst (engine-out) or post-catalyst (tailpipe), and introduce EGR using pulsewidth modulation if necessary.
5. Reiterate all steps if EGR is introduced in step 4 to ensure proper calibration.

Table 2. Engine Efficiency Testing Calibration Method

Experimental Procedure and Data Collection

Due to the programming characteristics of the engine management system, data collection techniques will be largely focused upon its calibration features. Some relevant terminology used in Emtech manual includes: "bar" - an operating reference interval of the manifold air pressure (MAP), "fuel map" - a calibration grid/graph of "bars" and fuel injection times distinguished by a reference RPM, "O2 loop" - the percentage correction of fuel injection time in order to operate at a stoichiometric fuel/air ratio.

1. Data Collection will be acquired at intervals of 500 RPM and two "bars" of MAP, from 1000 to 5500 RPM and for bars 32, 30, 28, ..., 12, 10 of MAP, assuming the operation of the engine is stable.
2. Testing will begin at the lowest untested RPM and MAP.
3. Testing will complete data collection for increasing MAP intervals of the lowest RPM, then increase the engine speed to the next RPM interval starting with the lowest MAP.
4. Actual data point test locations shall be maintained within 100 RPM and within the physical bounds of the MAP "bar" of the desired test grid.
5. Steady state operation of the engine will be maintained for 60 seconds to verify proper data point location and operating conditions.
6. Once steady state operation is verified, data collection will begin for both the engine management system and for the dynamometer DAS, which will take place for approximately 10 seconds (approx. 150 data points).
7. Once completed, the next data point location will be acquired and the procedure will repeat beginning with item 5 of this section.

Table 3. Engine Testing Data Collection Procedures

During the testing the data shown in Table 4 was recorded. Table 4 also indicates why the data was recorded

1. Fuel Injection Pulsewidth - Efficiency calculation requirement.
2. Dynamometer Torque - Efficiency calculation requirement
3. Manifold Air Pressure - Monitor
4. Angular Velocity – Efficiency calculation requirement
5. Control Room Temperature, Barometric Pressure, and Relative Humidity – For correction as per SAE J 1439
6. Coolant Temperature - Monitor

Table 4. Engine Testing Data Collection Values

Efficiency Calculations

The brake efficiency of the engine is determined from the following equation where the constants are various conversion factors for the units listed below.

$$h = \frac{\left(\frac{T \cdot n}{5252}\right)(0.7457)}{[f(x)]\left(3/2\right)(n)(u)(E)(60)}$$

Equation 2. Engine Efficiency Elemental Calculation

When reduced, the equation becomes:

$$h = \frac{(T)\cdot(1.5776)}{[3.2109(x) - 2.6602](u)}$$

Equation 3. Engine Efficiency Reduced Calculation

Where

- *T* - Torque (ft-lb)
- *n* - Angular velocity (RPM)
- *x* - Pulsewidth (ms)
- *f(x)* - Fuel mass as a function of pulsewidth x (mg)
- *u* - Fuel specific volume (gal/mg)
- *E* - Fuel volumetric energy content (kW-hr/gal)
- *u* - Fuel specific energy (kW-hr/kg)
- η - Engine efficiency (%)

Exhaust Gas Analyzer

The engine exhaust emissions were tested by a NOVA 7550P5B, five gas exhaust analyzer loaned to us by Lean Power Corporation, a Maryland Industrial Partner member. This model is designed to be transportable using common 115 VAC, 60 Hz power, providing a pump flow rate of 5 to 6 ft^3/hr. The analyzer tests for the following exhaust gases within the specified ranges.

CO	(0 - 10.00%)
CO_2	(0 - 20.0%)
HC	(0 - 2000 ppm)
NO_x	(0 - 5000 ppm)
O_2	(0 - 20.0%)

The oxygen sensor was not working during the tests, and consequently, O_2 emissions were not recorded in the engine data, however this did not affect other sample gas components since the oxygen sensor is independent of the other measurement techniques. All carbon based gas samples, CO, CO_2, and HC, are measured using a high precision infrared detector which conditions the internal analog signal through a 12-bit digital linearizer before registering the values on digital readouts. The linearizer provides more than 4,000 correction points over the range of each gas. NO_x is measured by separate NO and NO_2 sensors, and may displayed independently or collectively by a NO-NO_2-NO_x switch.

The exhaust analyzer was calibrated per instructions during the testing procedure, such that while sampling ambient air, the display readouts of all gas samples read zero. This assured that the exhaust gas measurements were net readings. Calibration of the exhaust gas analyzer was performed by Lean Power one month previous to the engine efficiency testing. The analyzer has one additional feature that was not completely available during this engine testing. For each gas measurement, analog output signal terminals are provided in the back of the instrument in order to connect it to datalogging equipment. For each of the gas ranges given above, the analog output provides a 0 - 1 V signal which can be recorded. Some data was collected in this manner for NO_x emissions. However, the infrared linearizer for CO, CO_2, and HC gas measurements did not have the required signal amplifier installed, so when these output terminals were connected to the datalogging equipment, all values switched to an irrelevant negative value, even the digital displays. Therefore, to obtain some relative engine emission values, all data, including the NO_x gas sample, were eventually recorded manually at steady-state operating points.

ELECTRIC MOTOR AND POLYCHAIN BELT EFFICIENCY TESTING

The electric motor used in this project was a Unique Mobility model DR 156s. This is a DC brushless motor with Neodymium Iron Boron magnets; a continuous torque output of approximately 17 ft-lb throughout its entire RPM range, and a voltage constant of 20V/1000 RPM. In the vehicle it operated from a 154 volt NiCd battery pack. When connect to the engine dynamometer for the efficiency testing, power came from a 440V AC motor / DC generator set located in the basement of the laboratory. The voltage output of the generator set was adjusted to 140 volts and monitored at the input to a Unique Mobility CR20-150 motor controller during testing. Current input was determined from an Empro 100A current shunt with an output of 1.97 mv/A. The electric motor was coupled directly to the engine dynamometer with a three piece Lovejoy (two steel jaws with a flexible rubber insert) coupling.

When in the vehicle, the electric motor was located parallel to the transmission with a shaft offset of approximately 15 inches. It was coupled to the input of the transmission via a Gates Polychain belt (a Kevlar reinforced, toothed timing type belt), two toothed pulleys and an overrunning clutch assembly. This equipment is fully described in Volume 8 of this study in the document named 95tech.doc. To better match the torque and RPM characteristics of the electric motor to that of the Suzuki engine, the electric motor RPM to input shaft transmission RPM ratio was 0.8 (with the bus voltage of 154V the electric motor was capable of operation to over 6000 RPM at full torque – this was far in excess of the maximum designed and optimized RPM of the Suzuki engine, and thus the 0.8 ratio would produce a RPM at the transmission of 4800).

For efficiency testing of the Polychain belt, the electric motor was used as the prime mover and was offset from the input of the engine dynamometer by the same 15 inches, but the ratios were reversed to better match the characteristics of the dynamometer. The same belt that was used in the car was tested on the engine dynamometer.

Electric Motor, Polychain Belt, and Dynamometer Setup

The basic configuration of the attachment of the electric motor to the transmission and to the engine dynamometer for belt efficiency testing is shown in Figure 4. The small pulley pitch diameter measured 4.010 inches, and the large pulley pitch diameter measured 5.013 inches with an effective gearing ratio of 1.25:1. Length between the pulley/belt tangents was approximately 15 in. Belt tension settings during the experiments were chosen by measuring the belt deflection at the midpoint of the pulley/belt tangents. Using Equation 4 below, the static belt tension can then be approximated and used as a reference point in efficiency measurement differences between belt tensions. Deflections tested during the experiment were 0.25, 0.39, 0.51, and 0.61 inches using a 10-lb weight, giving static belt tension approximations of 150, 96, 75, and 62 lb.

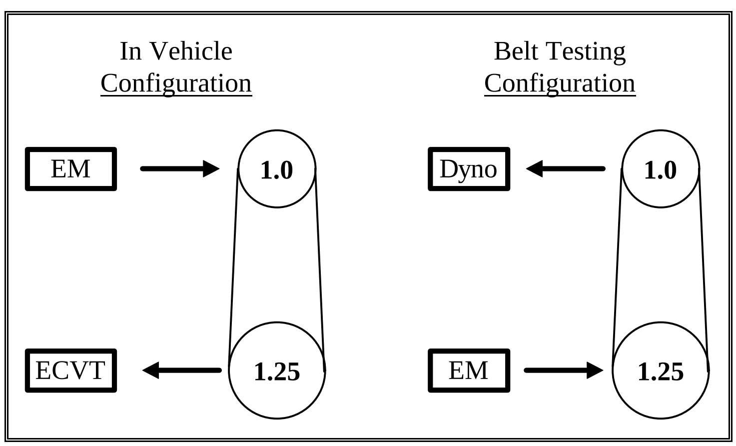


Figure 4. Belt Efficiency Testing vs. Vehicle Pulley Configuration

$$T = \frac{WL}{4d}$$

Equation 4. Indirect Belt Tension Measurement Calculation

- W - Weight of hanging mass (lb)
- L - Length between belt tangents (in)
- δ - Deflection of belt at the midpoint (in)
- T - Tension (lb)

Experimental Procedure and Data Collection

The electric motor or the combination of electric motor and belt were attached to the engine dynamometer, and measurements were made using the Daytronic DAS. As with the other tests, a typical run would last 10 seconds with a total of 150 data points which were then averaged to complete a data set for those particular conditions. The electric motor testing consisted of mapping increasing torque outputs vs. RPM, and the same was done with the belt testing with the additional variable of belt tension.

Efficiency Calculations

The efficiency of the electric motor and the Polychain belt was determined using equations 5 and 6 below. Equation 6 shows that the efficiency of the belt is dependent upon knowing the efficiency of the electric motor, which can be determined from earlier tests on the motor alone.

$$h_{EM} = \frac{T \cdot n}{V \cdot I \cdot (7.043)} = h_{EM\&B}{}^{**}$$

** Depending on setup

Equation 5. Electric Motor or EM/Belt System Efficiency Calculations

$$h_{B} = \frac{T \cdot n}{V \cdot I \cdot (7.043) \cdot h_{EM}}$$

Equation 6. Polychain Belt Efficiency Calculation

- T - Torque (ft-lb)
- n - Angular Velocity (RPM)
- V - Voltage (V)
- I - Current (A)
- η_{EM} - Motor/Controller Efficiency (%)
- η_{B} - Belt Efficiency (%)
- $\eta_{EM\&B}$- Combined Electric Motor & Belt Efficiency (%)

VEHICLE FUEL ECONOMY AND EMISSIONS TESTING

Rockwell WINtelligent LINX

This software accesses the Allen Bradley controller and enables the transfer of Allen Bradley data to a PC in real time. Another PC was used to record the Emtech engine data. In the analysis phase, both sets of data were time synchronized using Excel spreadsheets. It is thus possible to review the entire system operation during the UDDS and HWFET driving schedules. Typical results are presented in results and discussion sections.

Emissions Testing

The testing for the emissions was done at Environmental Research and Development Corporation located in the northern suburbs of Washington DC. This is an independent EPA certified laboratory with equipment conventionally found is such a facility. Eleven tests were conducted using UDDS, FTP – 75 and HWFET driving cycles. Normal procedures for cold soak, and other such preparations were performed before each of the tests.

ENGINE AND VEHICLE CONTROLLER EMULATION DESCRIPTIONS

EMTECH E6s ENGINE MANAGMENT SYSTEM

The engine management system used in the Saturn HEV was a unit purchased from Engine Management Technologies (Emtech), also known as Haltech or Injectech. The original six cylinder, batch fire, multi-port fuel injection and spark advance engine control unit (ECU) was modified by Emtech to operate a three cylinder engine using sequential, multi-port fuel injection and additionally control an exhaust gas recirculation (EGR) valve solenoid using pulsewidth modulation.

Software Calibration Options

As was mentioned earlier, the user via a PC connected through serial ports programs this unit. Table 5 lists the calibration features available.

Direct Calibration Parameter Adjustments

- Fuel Injector Pulsewidth [Time (ms) vs. MAP vs. RPM]
- Ignition Timing [Advance (°) vs. MAP vs. RPM]
- Exhaust Gas Recirculation [Modulation (%) vs. MAP vs. RPM]
- Cold Start Fuel Enrichment [Injection Increase (+ %) vs. Coolant Temp.]
- Cold Start Timing [Advance (+ °) vs. Coolant Temp.]
- Cold Start Priming Enrichment [Time (ms) vs. Coolant Temp.]
- Atmospheric Corrections [Injection (± %) & Advance (± °) vs. Air Temp.]
- Throttle Acceleration [Injector Increase (+ %) & Injector Sustain (+ %) vs. RPM]
- Closed Loop Fuel Control [Toggle Point (mV) & Limits (± %)]
- Idle Speed Control [Idle Speed (RPM), Cold Start Idle Increase (+ RPM), & Damping]

Indirect Calibration Assistance Features

- Real-Time Calibration Adjustments
- Real-Time Engine Data Monitoring
- 8 Hz Data Acquisition of 13 Parameters Selectable Via Two Screens

Table 5. Emtech E6s Software Features

ECU Operating Characteristics

The pulse width of the fuel injectors in ms is determined from Equation 7 described below.

$$PW = X_{BASE} + (X \cdot \%_{COOLANT}) + (X \cdot \%_{AIR}) + (X \cdot \%_{ACCEL}) + (X \cdot \%_{BATTERY}) + (X \cdot \%_{CLOSED}) + Y_{START}$$

$$X_{BASE} = X = f(MAP, RPM)$$

$$\%_{COOLANT} = f(Coolant\_Temp)$$

$$\%_{AIR} = f(Air\_Temp)$$

$$\%_{ACCEL} = f(Accelerator\_Pedal\_Rate, RPM)$$

$$\%_{BATTERY} = f(Battery\_Voltage)$$

$$\%_{CLOSED} = f(Oxygen\_Sensor\_Voltage, RPM, Accelerator\_Pedal\_Rate, Coolant\_Temp)$$

$$Y_{START} = f(RPM, Coolant\_Temp, Decay\_Rate)$$

Equation 7. Fuel Injector Pulsewidth Calculations

As can be seen, the pulse width is determined from a base pulse width which is a function of RPM and manifold absolute pressure, and then modified by six correction factors. These factors are functions of engine coolant temperature, air inlet temperature, rate of accelerator pedal change, plus several others.

The ignition timing determination is made from a base table that is a function of engine RPM and manifold absolute pressure, and then corrected for engine coolant temperature.

Important Calibration Parameters

Figures 5 through Figure 9 illustrate several of the programmable lookup tables the engine management system uses to determine the final fuel pulse width and the final ignition timing. Figure 5 shows the fuel injector pulse width in ms as a function of MAP (manifold absolute pressure) at 2000 RPM. The MAP axis has 32 divisions ranging from idle (at the left corresponding to 1) to wide-open throttle (on the right corresponding to 32). Similar tables were generated at 500-RPM increments (the finest graduation allowed in programming) during the dynamometer testing of the engine. The smallest change available to the fuel injection pulse width was 0.064 ms. The pulse width for engine operation between the discrete MAP or RPM intervals during regular operation is determined by interpolation.

Figure 6 shows the ignition-timing plot for 2000 RPM. At light loads, ignition timing is advanced in order to improve the fuel economy, and at greater loads it is retarded to prevent detonation. During the generation of this information on the engine dynamometer, the concept of minimum advance for best torque was used.

Figure 7 is a plot of the correction data used to increase the base fuel injection pulse width by a fixed percentage as a function of engine coolant temperature. A slight enrichment is necessary during warm-up to have smooth engine operation with no hesitation

Figure 8 is a plot of the spark advance vs. coolant temperature correction table. At high engine temperatures, the spark timing is retarded to reduce power and to prevent detonation. A cold engine needs additional enrichment during starting, and the calibration table for this information is shown in Figure 9.

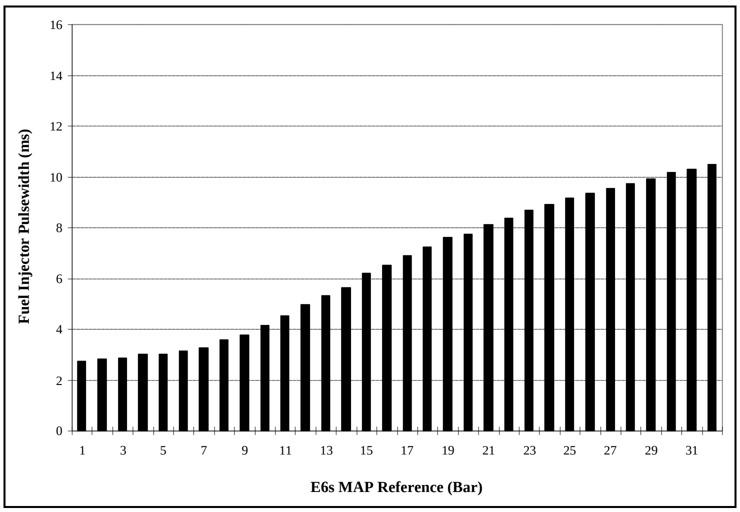


Figure 5. Fuel Pulsewidth Calibration Table for 2000 RPM

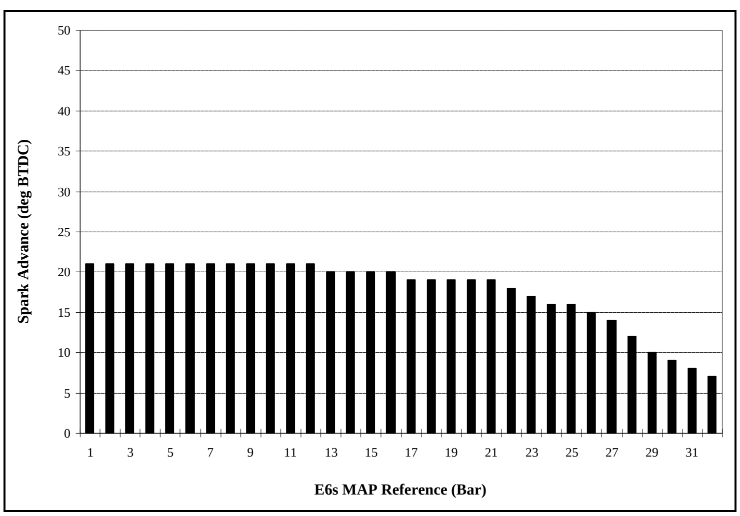


Figure 6. Spark Advance Calibration Table for 2000 RPM

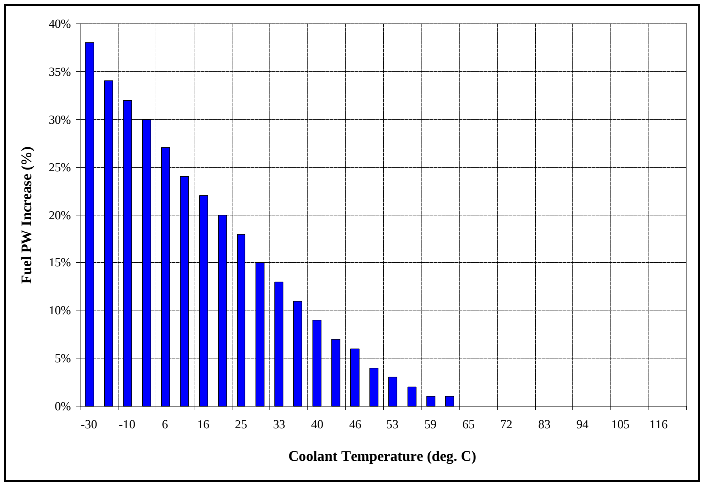


Figure 7. Fuel Pulsewidth Coolant Correction Calibration Table

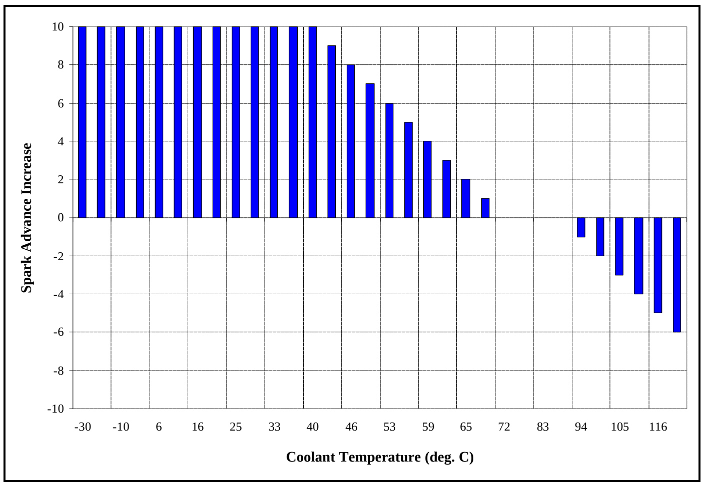


Figure 8. Spark Advance Coolant Correction Calibration Table

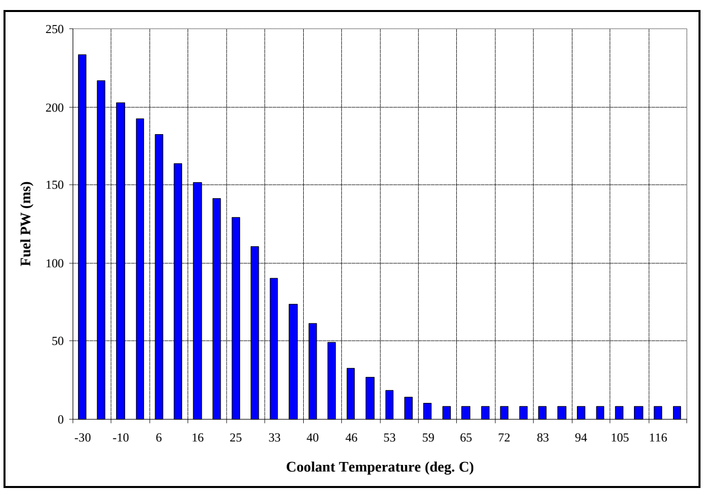


Figure 9. Cold Start Initial Fuel Pulsewidth Calibration Table

ALLEN-BRADLEY PROGRAMMABLE LOGIC CONTROLLER (PLC)

Allen-Bradley is a major manufacturer of programmable logic controllers for industrial applications. These applications require a very robust microprocessor and interface modules in demanding environmental conditions. Allen-Bradley was a sponsor of our 1994-96 hybrid electric vehicle teams, and their equipment was used as the basic system controller for this program. The equipment was located in two shoebox modules, one located under the dashboard and the other in the trunk. The processor was Allen-Bradley's SLC 5/03 controller module.

PLC Ladder Logic Basics

Programming of the PLC is done in a symbolic language known as ladder logic that is not normally taught or used at the University level. The PLC program is written using a PC and Allen-Bradley's software and then downloaded to an EPROM in the SLC 5/03 controller. The program is activated upon power up of the controller. All of the programs and references are given in Volume 2 of this report, but some of the basics of the language syntax are presented below. Essentially, all of the input and output signals are assigned memory addresses as well as the permanent look-up tables used for program execution. The program follows the symbolic rungs of a ladder from top to bottom (thus its name) with branching and logic considerations available at any point on the ladder.

Bit Instructions		
–| / |–	, XIO	Examine if Open:
–| |–	, XIC	Examine if Closed:
–( ) –	, OTE	Output Energize:
–(OSR)–	, OSR	One Shot Rising:
–(L)–	, OTL	Output Latch:
–(U)–	, OTU	Output Unlatch:

Timer & Counter Instructions		
– –	, TON	Timer On-Delay:
– –	, CTU	Count Up:
– –	, CTD	Count Down:
– –	, RES	Reset:

Comparison Instructions	
– – , EQU	Equal:
– – , LES	Less Than:
– – , LEQ	Less Than or Equal:
– – , GRT	Greater Than:
– – , GEQ	Greater Than or Equal:
– – , LIM	Limit Test:

Math Instructions	
– – , ADD	Add:
– – , SUB	Subtract:
– – , MUL	Multiply:
– – , DIV	Divide:
– – , SCL	Scale:

Move & Logical Instructions	
– – , MOV	Move:

Control Instructions	
– – , JSR	Jump to Subroutine:
– – , SBR	Subroutine:
–(MCR)– , MCR	Master Control Reset:

Table 6. PLC Ladder Logic Instruction Descriptions

Program Overview

In total, 38 numbered ladder files were used to operate the vehicle (some were deleted or renamed during the development, but for consistency and compatibility the vacant file placeholders were retained). The description of these files and their purpose is given in Table 6, and their complete ladder logic programs can found in Volume 2. Volume 3 provides additional detail as to the content of the PLC program, and in particular flowcharts the program logic in Visio.

SBR #	Filename	Description
2	SystemInfo	Initiates program and conditionally jumps to all other program subroutines.
3	Drivr_Info	Controls I.P. information for the speedometer, tachometer, etc.
4	Diagnostic	Organizes & stores diagnostic error code information.
5	TTL_Inputs	Qualifies multiple input switch information. (Ignition, mode, EHC, etc.)
6	Analog_In	Conditions all analog input signals into physical data.
7	Mode_Decsn	Enables components & driving modes for safe vehicle operation.
8		
9	LKP_Bits_1	Quantifies analog data into discrete intervals for lookup table files.
10	SOC_LKP	Lookup table for battery state-of-charge. (vs. voltage vs. current)
11	Batt_Effcy	Calculates a voltage efficiency using cell real-time voltage vs. SOC nominal.
12	SOC_Calctn	Contains SOC integrating algorithm using voltage efficiency & table X-ref.
13		
14		
15	TrqRequest	Interprets accelerator torque request under HEV, drive-by-wire. (HEV-DBW)
16	ICE_EM_LKP	Determines the nominal engine torque. (vs. SOC vs. speed for HEV-DBW)
17	HEV_Calctn	Computes the desired engine and electric motor torque levels for HEV-DBW.
18	_HEV_Back_	Computes the EM speed/regen output in accel/engine throttle HEV mode.
19	TrqOut_LKP	Data lookup table for engine torque output. (vs. RPM vs. MAP)
20	LKP_Bits_2	Quantifies analog data into discrete intervals for lookup table files.
21	TPS_LKP	Data lookup table for DBW engine throttle position. (vs. torque vs. RPM)
22	_ICE_Back_	Computes the EM speed/regen in accel/engine throttle ICE mode.
23	ICE_Only	Controls stepper motor position and EM speed/regen for ICE-DBW.
24	ELEC_Only	Computes the EM speed/regen vs. accelerator & brake. (torque controlled)
25	ICE_Charge	Controls stepper motor position and EM speed/regen for CHARGE-DBW.
26	ICE_Emissn	Operates engine emission components on vehicle/engine startup.
27	ICE_Start	Initiates automatic engine startup procedures.
28	HEVGeneral	Computes EM speed/regen output for HEV modes under torque control.
29	_CH_Back_	Computes EM regen output for accel/engine throttled CHARGE mode.
30	Test	Tests program changes separately from the original program.
31	Datalog	Compiles program referenced data for datalogging.
32	Swtchboard	Allows independent operation of select components via external switches.
33	Stpr_Motor	Exclusively controls stepper motor functions. (position and conn. testing)
34	Elec_Motor	Exclusively controls electric motor functions. (target speed, regen, & pre-spin)
35	ECVT_Trans	Exclusively controls transmission functions. (clutch & solenoid engagement)
36	1stPassOTU	Unlatches latched bit files during program execution and startup.
37	Relays_TTL	Conditionally enables PLC relays to become energized.
38	Zero_File	Resets all analog outputs to zero upon vehicle startup & emergency shutdown.

Table 7. PLC Program File Listing and Description.

System Control

The system software was written to load level the IC engine. This means that at light loads for a conventional vehicle, the IC engine will drive the vehicle and charge the batteries. At moderate loads the IC engine will drive the vehicle with a decreasing amount allocated to the battery. At high loads the IC engine and the electric motor will drive the vehicle. The transition sequence can be explained with the aid of Figure 10.

Using the efficiency maps of the various components, it was determined through steady-state simulation when and where to utilize the engine, the electric motor, or a combination of both, to yield the best possible system efficiency. The basic scheme was to maintain constant engine load at an efficient and battery charge sustaining torque level, while compensating for the driver's total powertrain torque request (accelerator position) with the electric motor. As an example, consider a desired constant engine load of 35 N-m with the accelerator pedal position corresponding as a direct total torque request (0% to 100% indicating 0 N-m to 100 N-m). For accelerator positions between 0% and 35%, the engine both drove the vehicle, and provided power to charge the batteries through the electric motor/generator as seen in Figure 10. Full generator capability (25 N-m) was employed between 0% and 10% accelerator, which then linearly decreased to 0 N-m at 35% accelerator position. Between 0% and 10% accelerator, the engine was required to increase its torque output from 0 to 35 N-m. Beyond 35%, the electric motor assisted the engine in driving the vehicle, with a linearly increasing torque assist up to full torque capability (25 N-m) at the 60% position of the accelerator pedal. Beyond 60%, the engine torque increased to its maximum output in order to match the driver's total torque request, the sum of the engine and electric motor/generator torque.

The speed of the vehicle and the state of charge (SOC) of the batteries, as indicated above, altered the desired constant engine load, and thus the control signal to the engine's throttle-controlling stepper motor. Engine torque was maintained relatively constant first by the constant RPM shifting of ECVT, and second by using the efficiency testing data to determine required engine throttle positions for desired torque output levels. The SOC was monitored by first measuring the battery voltage and current at one second intervals, and then computing a Whr change during this time. This Whr change was adjusted for battery voltage inefficiency by using experimentally derived, nominal voltage, lookup tables stored in the PLC's program. After the Whr number was adjusted, the accumulated energy was then calculated to include the latest interval and a new SOC was determined. Typically, higher vehicle speeds or low battery SOC would increase the constant engine load to maintain or increase battery SOC. The baseline constant engine torque value was determined to be 35 N-m for the vehicle to be charge sustaining over two UDDS driving cycles.

The IC engine and motor/generator controls were altered under the following conditions:

- SOC Modified Nominal IC Engine Torque
  - Greater than 80% SOC: 25 N-m engine torque
  - 40% to 80% SOC: 35 N-m engine torque
  - 30% to 39% SOC: 40 N-m engine torque
  - Less than 30% SOC: 45 N-m engine torque
- Vehicle Speed Modified Nominal Engine Torque
  - 0-20 mph: engine torque not greater than 20 N-m
  - Above 45 mph: increase engine torque by 10 N-m
- Voltage Dependent Electric Motor/ Generator Control
  - 0 motor assist at 100 volts, increasing up to nominal at 125 volts

- Begin decreasing regenerative braking at 195 volts; zero at 205 volts

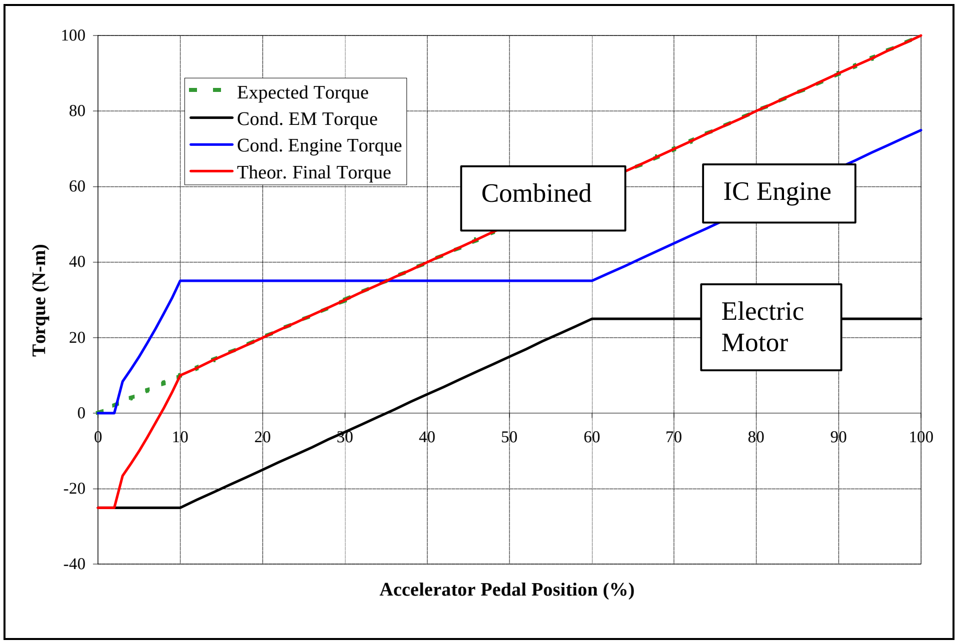


Figure 10. Overview of System Power Flow

RESULTS AND DISCUSSION

Since transmission, engine, electric motor, and belt efficiency testing were all performed in a similar manner using the engine dynamometer, testing results were evaluated in a similar manner as well. As mentioned previously in the experimental procedure section of this report, all four component tests were conducted at steady-state operating points for 15 seconds, providing approximately 150 data points for analysis. To evaluate this data, Excel macros were used extensively to provide consistent analysis calculations and result formatting.

<u>ELECTRONIC CONTINUOUSLY VARIABLE TRANSMISSION (ECVT) EFFICIENCY TESTING</u>

Efficiency Calculations Reviewed

For the sake of convenience, Equation 1 relating the efficiency of the transmission to the measurements is repeated below as Equation 8. During the analysis of the data, we discovered an error relating to the offset of the load cell measuring the torque at the engine dynamometer. A corrected efficiency of the transmission is represented by Equation 9.

$$h = \frac{(T_o + T_g)*(RPM_o / 6)}{(T_i * RPM_i)}$$

Equation 8. Transmission Efficiency Measurement Calculation

$$h_{CORR} = \frac{T_{IN} \cdot h_{ORIG}}{T_{IN} - T_{OFFSET}}$$

Equation 9. Efficiency Correction Calculation due to Load Cell Miscalibration

- T_o - Dynamometer torque (ft-lb)
- T_q - Gearbox torque (ft-lb)
- T_i - Engine torque (ft-lb)
- RPM_o - Dynamometer angular velocity (RPM)
- RPM_i - Engine angular velocity (RPM)
- η - Transmission efficiency (%)
- η_{CORR} - Corrected transmission efficiency (%)
- η_{ORIG} - Original transmission efficiency (%)
- T_{IN} - Recorded dynamometer torque (ft-lb)
- T_{OFFSET} - Calibration offset correcting torque (ft-lb)

Results and Analysis

Tables 8-11 show the transmission efficiency as functions of torque input, engine RPM transmission shift speed , pulley ratio, and in some cases repeated tests. The complete data files can be found in Volume 4 of this report, including the uncertainty percentages for 95 and 99% coverage as per ANSI/ASME Performance Test Code 19.1-1985. For 99% coverage the typical uncertainty at 50 and 60 ft-lb of torque was on the order of $\pm$ 2.5%, and at 20 ft-lb it was $\pm$ 4%. While at first glance, the repeated tests (most done on different days) don't seem to repeat very well, the results do fall within the uncertainty bands. Because of the uncertainty in the measurements, conclusions as to the best operating points are somewhat clouded, but some basic trends can be observed. These are: (1) - the transmission is more efficient at higher throughput torques; (2) – the transmission is more efficient at a pulley ratio of 1:1; (3) – the transmission is more efficient at shifting speed input speeds of 2000-3000 RPM (using the 1:1 ratio as the comparison). Overall, the transmission efficiency ranged from approximately 75% to 95%.

Torque (ft-lb)

ICE RPM	1500	1500	2000	2000	2000	2000	2000
TRQ/P.R.	*2.5*	*2.0*	*2.5*	*2.0*	*1.5*	*1.0*	*0.5*
50		88.9%		90.8%	92.1%	91.8%	91.6%
40		86.7%		85.0%	87.8%	93.1%	92.6%
30	84.1%	86.4%	82.1%	83.8%	85.9%	90.1%	92.8%
20	81.5%	83.8%	78.3%	81.5%	83.4%	87.4%	87.8%
10	68.7%	74.1%					
30	84.4%	86.6%		87.1%	90.0%	90.8%	95.0%
20	80.8%	82.5%	85.1%	86.9%	89.1%	92.3%	94.7%
10	75.2%	74.6%	81.8%	84.5%	87.7%	91.7%	91.0%

Table 8. Transmission Efficiency, 1500 and 2000 RPM Engine Speed

Torque (ft-lb)

ICE RPM	2500	2500	2500	2500	2500
TRQ/P.R.	*2.5*	*2.0*	*1.5*	*1.0*	*0.5*
70			90.1%	92.3%	
60		87.8%	90.3%	92.4%	92.3%
50		85.6%	87.9%	90.0%	89.1%
40	92.1%	85.5%	86.4%	90.5%	90.9%
30	87.8%	81.2%	83.8%	87.9%	88.0%
20	85.9%	76.9%	78.5%	86.1%	86.0%
40	85.4%	87.9%	89.5%	91.0%	93.4%
30	81.1%	84.5%	87.2%	91.0%	91.0%
20	78.2%	80.7%	83.3%	89.1%	89.1%

Table 9. Transmission Efficiency, 2500 RPM Engine Speed

Torque (ft-lb)

ICE RPM	3000	3000	3000	3000	3000	3500	3500	3500	3500
TRQ/P.R.	*2.5*	*2.0*	*1.5*	*1.0*	*0.5*	*2.5*	*2.0*	*1.5*	*1.0*
60		88.4%	89.4%	90.3%	89.1%		83.0%	85.3%	88.4%
50		90.0%	88.9%	90.5%	87.6%	82.3%	83.3%	84.6%	87.0%
40	84.0%	85.4%	86.3%	88.4%	84.8%	79.5%	81.6%	83.4%	87.9%
30	81.5%	82.9%	84.0%	86.8%	82.7%	78.6%	79.3%	81.9%	85.0%
20	77.2%	79.0%	78.9%	82.9%	78.4%	72.3%	74.4%	75.9%	81.4%
50		88.2%	91.3%	92.3%	89.9%				
40	86.2%	87.6%	88.8%	90.5%	86.7%	82.1%	84.1%	86.4%	89.6%
30	84.7%	86.6%	87.9%	89.0%	85.3%	82.4%	83.4%	85.9%	87.0%
20	82.5%	84.3%	85.6%	87.9%	79.5%	77.5%	80.5%	82.4%	86.2%

Table 10. Transmission Efficiency, 3000 and 3500 RPM Engine Speed

	ICE RPM	4000	4000	4000	4000	4500	4500	4500
	TRQ/P.R.	*2.5*	*2.0*	*1.5*	*1.0*	*2.0*	*1.5*	*1.0*
	70			87.7%	87.2%			87.7%
Torque (ft-lb)	*60*			87.5%	88.4%		86.4%	88.8%
	50	82.4%	87.2%	84.2%	86.8%	83.2%	81.5%	83.4%
	40	80.2%	82.8%	83.1%	84.2%	82.5%	78.5%	79.6%
	30	75.4%	75.9%	78.6%	83.7%	80.8%	69.4%	71.2%
	40	86.3%	84.2%	85.7%	86.7%			
	30	78.1%	80.0%	82.0%	85.4%			

Table 11. Transmission Efficiency, 4000 and 4500 RPM Engine Speed

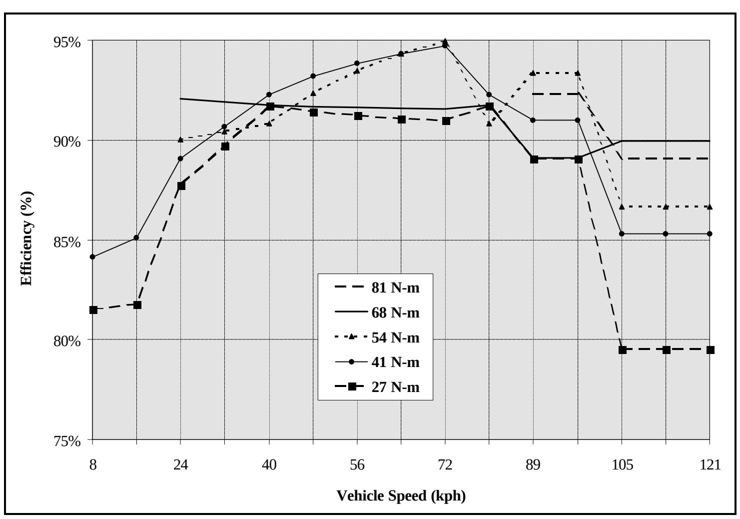


Figure 11. Transmission Efficiency at Various Vehicle Speeds, 2000 RPM Engine Shift Speed

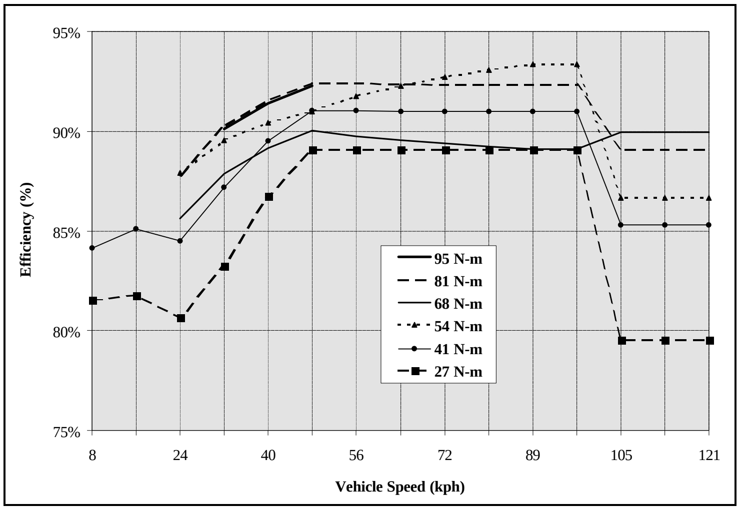


Figure 12. Transmission Efficiency at Various Vehicle Speeds, 2500 RPM Shifting Speed

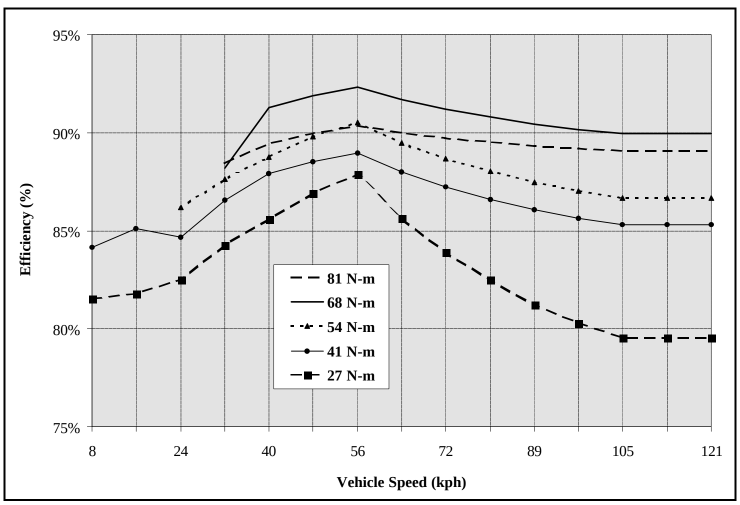


Figure 13. Transmission Efficiency at Various Vehicle Speeds, 3000 RPM Engine Shifting Speed

<u>**METHANOL-FUELED, INTERNAL COMBUSTION EFFICIENCY TESTING**</u>

Efficiency Calculations Reviewed

Equation 3 determining the efficiency of the IC engine is repeated below as Equation 10.

$$h = \frac{(T)\cdot(1.5776)}{[3.2109(x) - 2.6602](u)}$$

Equation 10. Engine Efficiency Reduced Calculation

- *T* - Torque (ft-lb)
- *x* - Pulsewidth (ms)
- *u* - Fuel specific energy (kW-hr/kg)
- η - Engine efficiency (%)

Analysis Worksheet Description

Volume 5 of this report contains the complete description of the information used to determine the efficiency of the engine, along with a considerable amount of material logged during the testing related to operating parameters. As equation 10 shows, the essential measurements are torque, fuel injector pulse width, and the specific energy of the fuel.

Table 12 lists the sources of information used during the analysis of the data. Some information was collected automatically, while other information needed to be entered manually. Excel worksheets were then used to compute the final results.

Daytronics DataPac

7. Dynamometer Torque
8. Dyno Torque Precision Index
9. Dynamometer RPM
10. Dyno RPM Precision Index
21. GM MAP Sensor Voltage
22. GM MAP Sensor Prec. Index
26. Control Room Bar. Pressure
27. Control Room Temperature
28. Engine Room Relative Humidity
34. NOx Emissions
35. NOx Prec. Index
36. Test File Names
37. Test Date & Time

Emtech Software Datalogging

11. ECU Reference RPM
12. Test Fuel Injector Pulse Time
13. Test FI Pulse Precision Index
14. Test FI Pulse O2 Correction
15. Test O2 Correction Prec. Index
16. O2 Sensor Voltage
17. O2 Sensor Voltage Prec. Index
18. ECU Manifold Air Pressure
19. ECU MAP Prec. Index
20. MAP Bar Reference
23. Throttle Position (%)
24. Manifold Air Temperature
25. Engine Coolant Temperature
29. Testing Spark Advance

Manual Input

4. Fuel Energy Analysis Info
5. Test Conditions Effic. Corrections
30. Engine Out HC Emissions
31. Engine Out CO Emissions
32. Engine Out NOx Emissions
33. Engine Out CO2 Emissions

Excel Calculations

1. Final Test Efficiency
2. ADD (99%) Uncertainty
3. RSS (95%) Uncertainty
6. SAE Corrected Dyno Torque

Table 12. Engine Efficiency Data Analysis Sources

Data Collection Results and Analysis

Table 13 shows the measured brake efficiency of the M85 engine, corrected for standard atmospheric conditions as per SAE J1349. The 99% bracket uncertainty at 60 ft-lb and 3500 RPM was 1.75%, and at 10 ft-lb and 3000 RPM it was 3.01%.

Torque (ft-lb)

TRQ / RPM	*1000*	*1500*	*2000*	*2500*	*3000*	*3500*	*4000*	*4500*
60						31.1%		
55				31.2%	31.1%	30.6%		
50		29.4%	30.2%	30.7%	30.5%	29.4%		
45		29.0%	29.4%	29.8%	29.7%	28.9%	25.6%	
40		28.4%	29.0%	29.3%	28.7%	28.2%	25.7%	22.4%
35		27.5%	27.9%	28.2%	27.5%	27.3%	25.8%	23.2%
30		26.5%	26.6%	26.8%	26.7%	26.1%	24.7%	22.8%
25		25.3%	25.1%	25.0%	25.2%	24.4%	22.6%	20.9%
20		22.9%	23.8%	23.9%	23.6%	22.8%	21.1%	19.0%
15		19.9%	20.6%	21.1%	21.3%	19.9%	19.1%	17.9%
10		16.5%	16.7%	16.8%	16.8%	15.8%	15.1%	14.8%
5	11.8%	11.18%	10.71%	11.78%	11.28%	10.20%	9.50%	8.40%

Table 13. Methanol Engine Brake Efficiency

The information in Table 13 has been plotted in Figure 14 below. The peak efficiencies are good for a normally aspirated spark ignition engine. Comparative data of this type is difficult to obtain, but by comparison we are aware of a marine 4 cylinder Suzuki engine that has been reported to have an efficiency of 34%. Also, the latest generation of small CIDI engines from Europe have been reported to have efficiencies in the mid 40's.

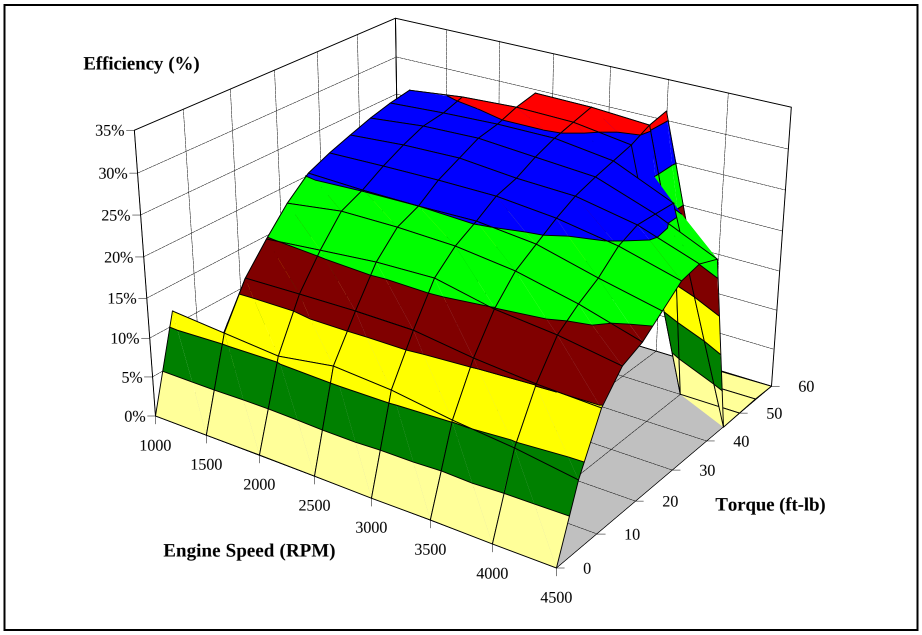


Figure 14. Methanol Engine Brake Efficiency

Injector Timing Reduction of Hydrocarbon Emissions

While testing the engine on the dynamometer, significant differences were noted in the emissions of the hydrocarbons in reference to injector timing. The recommendation by the injector manufacturer, Siemens, was that the injector should open and close before the valve opens. Otherwise there will be a change in the MAP (manifold absolute pressure) at the injector due to a surge of air. Therefore the MAP would be different at the injector than at the plenum, causing an unknown performance of the injector. (Note: this engine as well as all other multiport fuel injected engines we are familiar with employ a fuel rail pressure regulator. The regulator is connected to the intake plenum, and as the intake manifold pressure changes during normal operation, the fuel rail pressure follows so as to maintain a constant pressure difference across the inlet and outlet ports of the injector.)

The HC emissions versus injection timing were taken at an engine speed of 2500 RPM and an injection time of 12 ms. The injector timing corresponded to an output of approximately 45 ft-lb.; the maximum output at this RPM was 58 ft-lb. The results of the testing are illustrated in Figure 15. This Figure is complex and needs some explanation. Top Dead Center (TDC) on the compression stroke is located at the far-left end of the Figure at the axis position of –360 degrees. For the moment, please ignore the emission data as you follow the valve opening curves by moving along the horizontal axis from left to right. Near the bottom of the expansion stroke at –227 degrees (or 133 degrees after TDC) the exhaust valve begins to open, and is fully open at –110 degrees: at this point the piston is moving back up on the exhaust stroke. The point TDC' is known as the overlap TDC because both the intake and exhaust valves are open. The piston now heads down on the intake stroke and the intake valve is fully open about 112 degrees after TDC'. At 224 degrees after TDC' the intake valve is fully closed.

The baseline testing was done with the fuel injector pulse beginning at the initial opening of the intake valve. As can be seen from Figure 15, the injector pulse width nearly occupied the entire time the intake valve was open, and the HC emissions were recorded at 340 PPM (parts per million). It might be helpful to note that the entire sequence from –360 degrees to +360 degrees occupies 48 ms at 2500 RPM when converted to the time base. In the next test, the injector timing was adjusted so that the injector closed at the beginning of the intake valve opening, and the recorded data indicated a reduced HC emissions level of 130 PPM. The next test closed the injector 20 crankshaft degrees before the intake valve opened, and the HC emissions were further reduced to 60 PPM. Thinking, "more was better", the last test was conducted when the injector closed 40 crankshaft degrees before intake valve opening. However, in this case the HC emissions increased slightly to 80 PPM.

From these basic four tests it is apparent that there is an optimum time for the fuel injection pulse to occur in order to minimize emissions, and the closing point may be the key factor.

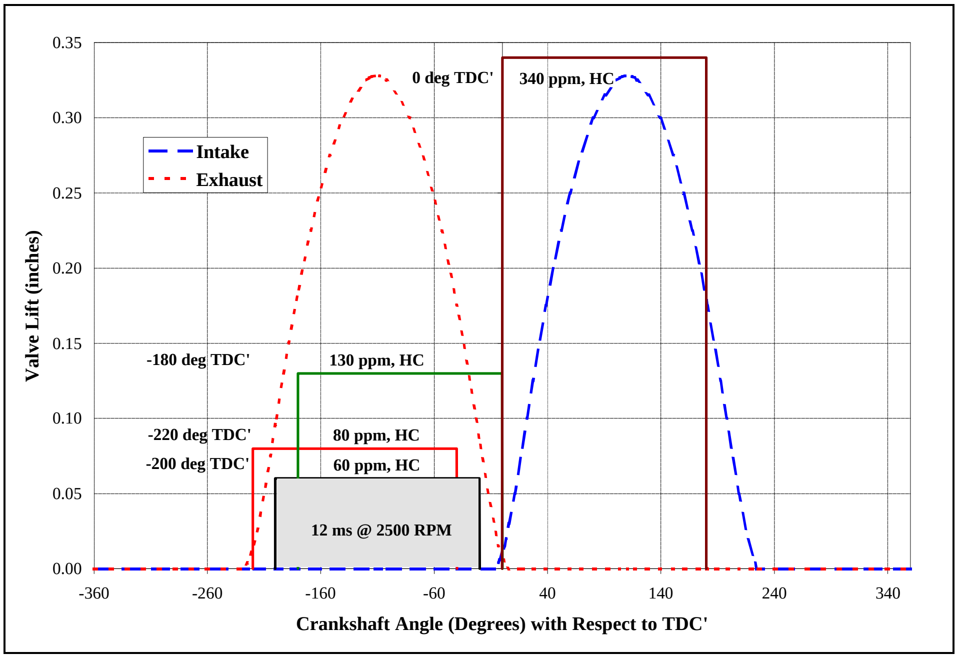


Figure 15. Sequential Multi-port Fuel Injector Timing Emission Results

ELECTRIC MOTOR AND POLYCHAIN BELT EFFICIENCY TESTING

Efficiency Calculations Reviewed

For the sake of convenience Equations 5 and 6 are repeated below as 11 and 12. The constants appearing in them are the result of conversions used in the equations with the units of measure listed below Equation 12.

$$\eta_{EM} = \frac{T \cdot n}{V \cdot I \cdot (7.043)} = \eta_{EM\&B}{}^{**}$$

Equation 11. Electric Motor or EM/Belt System Efficiency Calculation

$$\eta_{B} = \frac{T \cdot n}{V \cdot I \cdot (7.043) \cdot \eta_{EM}}$$

Equation 12. Polychain Belt Efficiency Calculation

- T - Torque (ft-lb)
- n - Angular Velocity (RPM)
- V - Voltage (V)
- I - Current (A)
- η_{EM} - Motor/Controller Efficiency (%)
- η_{B} - Belt Efficiency (%)
- $\eta_{EM\&B}$- Combined Electric Motor & Belt Efficiency (%)

Table 14 presents the results of testing the motor and controller. The efficiencies are not as high as those reported in Unique Mobility's data sheet. We believe the differences to be due to the difference in testing voltages. Unique's data is for a 180 volt bus, and our data is for a 140 volt bus. Further analysis of the differences in the data can be found in Volume 6 of the report.

Torque (ft-lb)

TRQ / RPM	*250*	*500*	*1000*	*1500*	*2000*	*2500*	*3000*	*3500*	*4000*	*4500*	*5000*	*5500*	*6000*
1	28%	41%	49%	51%	52%	54%	52%	51%	53%	52%	53%	54%	57%
2	39%	50%	57%	61%	63%	66%	66%	66%	67%	68%	67%	71%	73%
3	43%	53%	62%	67%	68%	70%	72%	73%	74%	74%	75%	77%	77%
5	45%	57%	67%	72%	74%	76%	78%	79%	81%	81%	80%	83%	83%
7.5	45%	57%	68%	74%	76%	79%	80%	82%	83%	85%	85%	86%	85%
10	41%	55%	68%	73%	76%	79%	81%	83%	84%	86%	85%	86%	87%
12.5	39%	53%	66%	73%	76%	79%	80%						
15	36%	50%	64%	71%	73%								
17.5	35%	48%	63%	67%									

Table 14. Electric Motor and Controller System Efficiency

This data has been plotted in a three dimensional format in Figure 16.

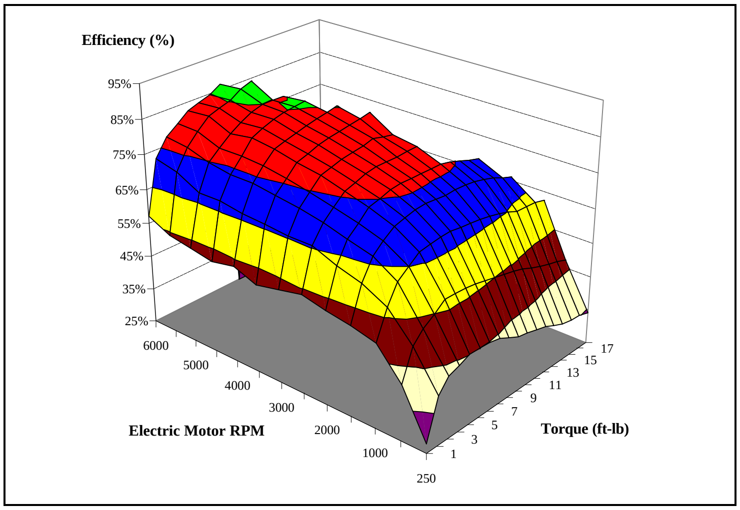


Figure 16. Electric Motor and Controller System Efficiency

As was described previously, the efficiency of the belt system coupling the electric motor to the overriding clutch assembly on the input shaft of the transmission was determined by driving the belt configuration on the dynamometer with the electric motor, and then correcting the results by the known efficiency of the electric motor at the chosen operating points.   The related Equation is 12. The belt was tested at pretensions of 62, 75, 96 and 150 lbs. Table 15 shows the results of those tests as a function of torque transmitted, belt tension and rpm.   The following general trends apply to the data: the belt system is more efficient with increasing amounts of transmitted torque; and the belt system is more efficient with decreasing amounts of belt pretension. This data however is rather noisy: at low torque levels, the 99% uncertainty level exceeds 10%. The situation gets somewhat better at higher torque levels where the 99% uncertainty is 3-4%

Torque (ft-lb)	Tension (lb)	***RPM***											
		310	***625***	***1250***	***1875***	***2500***	***3125***	***3750***	***4375***	***5000***	***5625***	***6250***	***6875***
2	***62***		76%	72%	70%	72%	73%	71%					
	75	67%	73%	65%	68%	70%	70%	66%	63%	64%	67%	61%	61%
	96	68%	69%	63%	58%	67%	64%	63%	64%	68%			
	150			64%	61%	66%	64%	63%					
4	***62***	87%		83%	84%	84%	84%	83%	83%		83%	84%	83%
	75	82%	83%	80%	83%	82%	82%	80%	79%	79%	80%	80%	79%
	96	75%	76%			79%	80%	77%	77%	78%			
	150	78%		79%	77%	71%	77%	76%	76%	76%	74%	76%	75%
6	***62***		88%	87%	89%	89%	87%	88%	88%	89%	88%	89%	
	75	89%	86%	86%	87%	87%	87%	86%	86%	86%	86%	86%	83%
	96	90%	84%	81%	85%	84%	84%	83%	82%	84%			
	150		85%	85%	84%	84%	84%	83%	83%		83%	83%	
8	***62***	96%		90%	91%	91%	91%	90%	89%	90%			
	75	92%	90%	90%	91%	90%	90%	88%	88%	89%			
	96	90%	84%			86%	86%	84%	85%				
	150			86%	88%	81%	87%	85%	84%	90%			
10	***62***		91%	92%	94%								
	75	97%	92%	91%	94%								
	96	93%	80%	87%	88%								
	150		91%	90%									
12	***62***	96%	93%										
	75	91%	92%										
	96	89%	90%										
	150	95%	91%		92%								

Table 15 . Polychain Efficiency as Function s of Torque, Belt Tension and RPM

The combined system efficiencies of the electric motor and the belt combination are given in Table 16. These results are the averages of three tests conducted at a pretension of 75 lbs. This same information is plotted in Figure 17. . Unfortunately, not enough belt tests were conducted at the higher torque and rpm levels. However, based on the control strategies employed and the normal operating rpm of the IC engine, combined efficiencies were nominally 65% or greater. These efficiencies numbers are not very good, and deserve consideration in future studies.

.

Torque (ft-lb)

TRQ / RPM	*260*	*520*	*1040*	*1560*	*2080*	*2600*	*3125*	*3650*	*4170*	*4690*	*5210*	*5730*	*6250*
2	29%	39%	41%	46%	49%	50%	49%	48%	49%	53%	47%	49%	47%
4	37%	48%	54%	60%	62%	63%	63%	64%	65%	66%	66%	67%	65%
6	38%	48%	59%	64%	66%	69%	69%	71%	72%	73%	73%	73%	73%
8	37%	49%	60%	66%	69%	71%	72%	73%	76%				
10	36%	48%	59%	67%									
12	32%	45%											
14		44%											

Table 16. Electric Motor & Polychain Belt Combined Efficiency, Test Reference Q,S,V – 75 lb Belt Tension

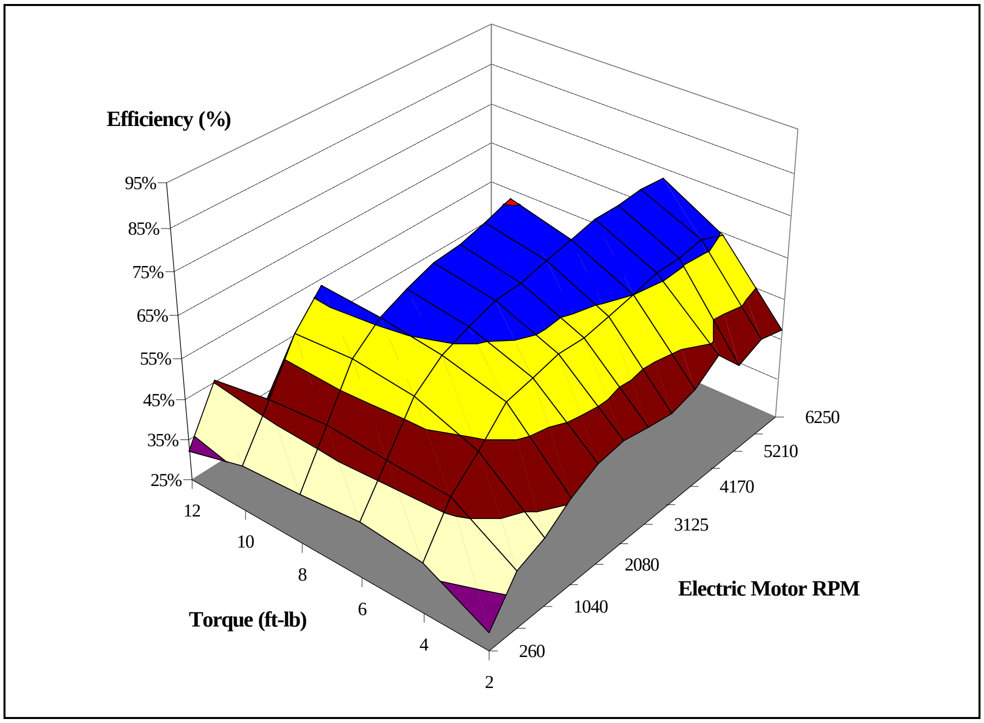


Figure 17. Electric Motor & Polychain Belt Combined Efficiency, Tests O, S,V

VEHICLE FUEL ECONOMY AND EMISSIONS TESTING

Graphic Analysis Description

To present the PLC's WinLinx captured data, a repetitive graph analysis was performed on the data according to the driving schedule, either an Urban Dynamometer Driving Schedule (UDDS), a 505 Schedule, or a Highway Fuel Economy Test (HWFET). If a ten minute hot soak occurred during a test, such as a Federal Test Procedure (FTP) consisting of a UDDS followed by a 505, the data was collected in separate Excel worksheets and accordingly analyzed separately using the repetitive graph analysis. Below, the repetitive graph analysis is listed in detail for both the UDDS and HWFET driving schedules. For each of the graphs, the prescribed vehicle speed has been synchronized to the WinLinx data and graphed in addition to all of the data listed below. In all of the graphs, the vehicle speed is plotted on the primary Y-axis, except in the Voltage & EM Limit graph, where the vehicle speed is plotted on the secondary Y-axis. Additionally, all data for both driving schedules is plotted using the Excel line graph format such that the X-axis label can serve closely as a time reference in seconds.

Urban Dynamometer Driving Schedule (UDDS) or 505 Schedule

1. Coolant, SOC, & O2 Sensor - Coolant Temperature (°C) [Primary Axis], State-of-Charge (%) [Primary], Oxygen Sensor Voltage (V) [Secondary].
2. SOC & Battery Energy - State-of-Charge (%) [Primary], Direct Battery Energy Usage (W-hr) [Secondary], Direct Battery Current Usage (A-min) [Secondary].
3. Engine Emission Components - Coolant Temperature (°C) [Primary], Accessory Battery Voltage (V) [Secondary], Heat Battery Switch (On/Off) [Secondary], EHC Ignition Switch (On/Off) [Secondary], Air Pump Switch (On/Off) [Secondary].
4. ICE Throttle & Nominal Trq - Nominal Engine Torque (N-m) [Primary], Engine Throttle Position (%) [Secondary].
5. Engine RPM & MAP - Engine Intake Manifold Air Pressure (kPa, differential) [Primary], Engine Speed (RPM) [Secondary].
6. Voltage & EM Limit - Battery Pack Voltage (V) [Primary], Voltage Dependent Electric Motor Programming Torque Limit (%) [Primary], State-of-Charge (%) [Secondary], Constant 195 V (Max. Voltage before Torque Limiting) [Primary].
7. Accel Pedal & ECVT Sol. - Accelerator Pedal Position (%) [Primary], ECVT Line Pressure Solenoid Switch (On/Off) [Secondary], Constant 55 N-m (Max. ECVT Input Torque with Solenoid On) [Primary].

Highway Fuel Economy Test (HWFET)

1. Speed, SOC, & Batt Energy - PLC Recorded Vehicle Speed (mph) [Primary], State-of-Charge (%) [Primary], Direct Battery Energy Usage (W-hr) [Secondary], Direct Battery Current Usage (A-min) [Secondary].
2. Accel, Coolant & Nom. Trq - Accelerator Pedal Position (%) [Secondary], Coolant Temperature (°C) [Primary], Nominal Engine Torque (N-m) [Primary].
3. Engine RPM & Throttle - Engine Speed (RPM) [Secondary], Engine Throttle Position (%) [Primary].
4. Engine RPM & MAP - Engine Speed (RPM) [Secondary], Engine Intake Manifold Air Pressure (kPa, differential) [Primary].

Table 17. Vehicle Fuel Economy/Emissions Testing Graphic Analysis Worksheets

Data Collection Results and Analysis

Typical results from the combined Excel spreadsheets from data taken during testing are presented in Figures 18 and 19. More complete results can be found in Volume 7 of this report and in the file WIN DATA.ZIP. In Figure 18, the lower plot is the vehicle speed over the UDDS cycle, the middle line is the battery SOC and the top line is the engine coolant temperature.

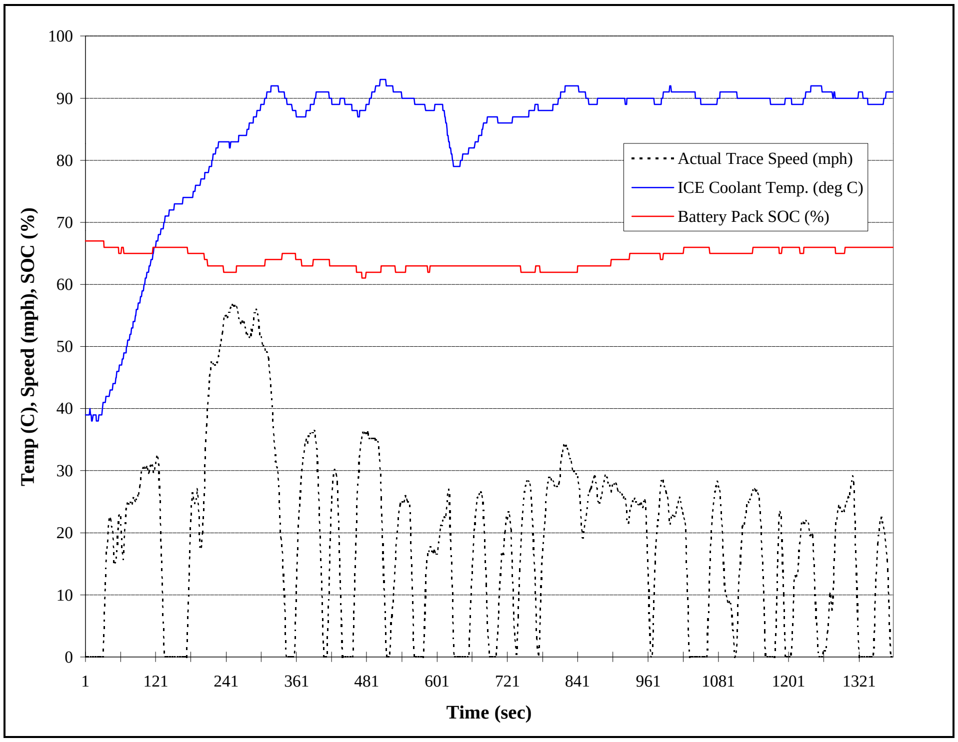


Figure 18. Engine Temperature, Battery SOC, and Vehicle Speed for a UDDS Test

Figure 19 shows some typical results for HWFET tests done on 5/23/97. The upper line is battery SOC, the next line is W-hrs, the next is vehicle speed for this cycle, and the bottom line is A-min. The W-hr plot and the A-min plot were derived directly from data logged from the controller and start at values determined from prior testing. These quantities were determined from the instantaneous measurements of battery voltage, battery current and time. The battery SOC plot is a calculation that takes into account the above data plus the inefficiencies of the battery pack at various current charge and discharge levels. During the last highway cycle of Figure 19, the vehicle achieved 75.3 mpg (gasoline equivalent) at a zero change in the battery state of charge.

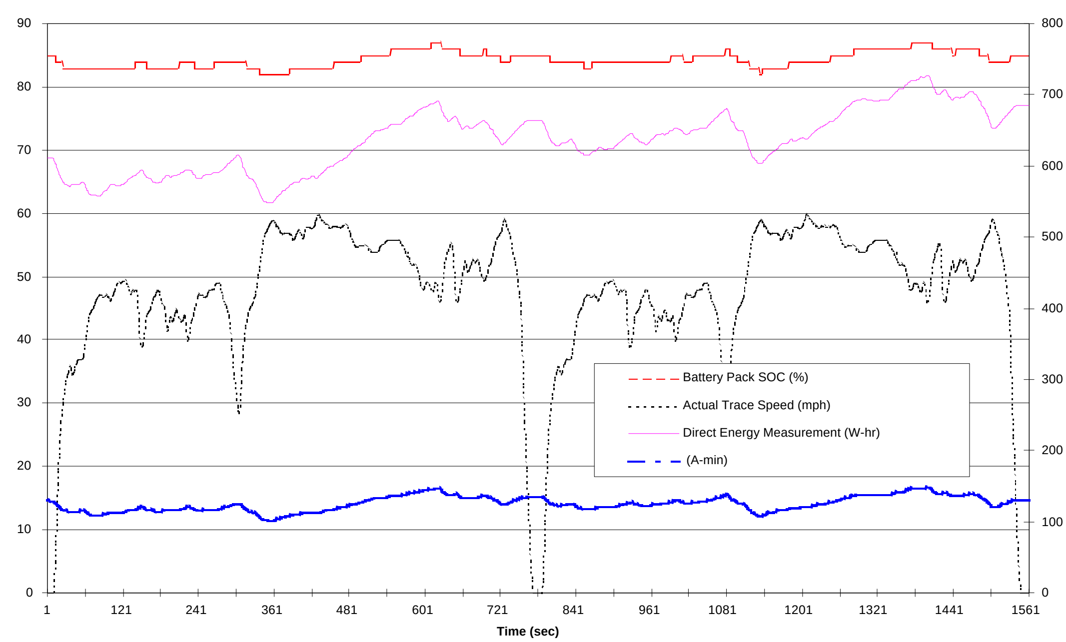


Figure 19. Battery SOC, W-hrs, Vehicle Speed, and A-min during a HWFET test.

CONCLUSIONS

ELECTRONIC CONTINUOUSLY VARIABLE TRANSMISSION (ECVT) EFFICIENCY TESTING

The efficiency of this transmission ranged from 75% to near 95% depending on the throughput torques, vehicle speed, and input shifting speed. It was highest at a vehicle speed of 60 KPH with an input shifting speed of 2000 RPM, and lowest at combinations or low or high vehicle speed along with an input shifting speed of 3000 RPM. In general, the greater throughput torques yielded the highest efficiencies. This last result is to be expected since the internal losses (such as hydraulic pump, bearing, and fluid turbulence) tend to remain relatively constant over a wide range of operating conditions.

METHANOL-FUELED, INTERNAL COMBUSTION ENGINE EFFICIENCY TESTING

The IC engine used in this project started out as a Suzuki 1L, which used gasoline throttle body fuel injection. It was extensively modified by raising the compression ratio to 12.5:1 via custom aluminum pistons, by employing tuned tubular intake and exhaust manifolds to optimize its efficiency at 3500 RPM, and by installing and programming a sequential multi-port fuel injection system. At various stages of the program the engine ran on M85 (early) and then E85 (late). In both cases, the engine calibrations were determined by cradled engine dynamometer testing where both the fuel injection and ignition timing were varied. A maximum efficiency of slightly over 31% (BTUs /sec)/ (bhp) * conversion factors was reached at wide-open throttle at 3500 RPM. At this point the engine was producing 60.7 ft-lb (82 N-m) of torque and 40.7 bhp (30.4 kW). The lowest efficiencies were at low power output combined with high and low RPM.

ELECTRIC MOTOR AND POLYCHAIN BELT EFFICIENCY TESTING

This combination is capable of operation to 200V with a continuous rating of 21.2 bhp (15.8 kW) at 6750 RPM. In this project with the lower battery bus voltage of 154 volts, the motor rating was 17.5 bhp (13 kW). Measured maximum efficiencies of the combined motor and controller were 87% at 6000 RPM and at an output torque of 10 ft-lb (13.5 N-m). Slightly higher efficiencies are possible (low 90%) with increased bus voltage and torque output.

Gates Polychain Belt

The Unique motor/generator was coupled to the input shaft of the Subaru transmission through a Gates Polychain belt and a Dana AL 20 overriding clutch assembly. The inputs to the transmission were both the IC engine and the electric motor/generator. The clutch worked in the following way: if the RPM of the IC engine was greater than that of the motor/generator, then the IC engine drove both the transmission and the motor/generator; if the RPM of the motor/generator was greater than that of the IC engine then it alone powered the transmission. During regenerative braking when the IC engine RPM was low, power would flow back through the motor/generator to charge the batteries.

The efficiency of the belt drive depends on the initial tension set on the belt, and the torque transmitted by the belt. The greatest efficiencies were obtained at a pretension of the belt set to just prevent it from jumping teeth when transmitting the maximum amount of torque from the motor. This efficiency was on the order of 92%.

SYSTEM CONTROL

The vehicle system was controlled using an Allen-Bradley SLC 5/03 controller and components. Thirty five files were written in ladder logic and programmed into the controller to operate the vehicle. The basic operating strategy was to load level the IC engine, and to make the vehicle a charge-sustaining hybrid. The accelerator pedal position was used as a basic torque command to the controller, which in turn operated the IC engine and the electric motor in a manner to maximize the overall system efficiency. Preset IC engine torque output levels were modified by vehicle speed, and the battery state of charge (SOC).

VEHICLE FUEL ECONOMY AND EMISSIONS TESTING

The completed vehicle was tested at Environmental Research and Development, an EPA certified laboratory. Eleven tests were conducted including UDDS, FUDS & HWFET. On the FTP driving schedule, the vehicle achieved 43 mpg gasoline equivalent (with a 4% decrease in the state of charge of the batteries) and on the HWFET, a 75 mpg equivalent (with a 0% change in the state of charge of the batteries). This amounts to a 65% improvement in the vehicle's baseline fuel economy in the FTP cycle and an 83% improvement in the highway cycle using the unadjusted data from EPA's 1992 database (the first year EPA had data for the Saturn). However, while CO emissions were below the most stringent 1997 California ULEV emissions, the HC emissions were at the Federal tier 1994 levels, and the NO_x emissions were at the Federal 1975 levels.

APPENDIX

All of the electronic data sent in completion of the UMCP/DOE contract, is contained in one compressed file entitled All.zip. The organization of this file may be viewed with any Pkzip® compatible software. The electronic file has been organized in such a manner as to reflect how the data was originally sent to the NREL FTP site. As all the files are extracted from All.zip using the directory information contained within, one should view 11 individual data files in the '/UMD-NREL Research Files' main directory along with 23 secondary directories, such as '/3honors', '/95tech', etc. Each of the secondary directories contains its own compressed file. Decompressing each of these zip files using the stored directory information will in turn extract more relevant data files and create new sub-directories with more compressed files if necessary.

To use the directory information contained in All.zip and all of its subsequent compressed files, one should continue using the main directory containing All.zip as the indicated software extraction directory. Below is a listing of the compressed files with directories, files, and file size information in their fully extracted form. A collection of tables follows this list, grouping the files into seven categories relating to the contract requirements. Following the group of tables and so ordered, each file is described in brief detail to explain its information role. Printed copies of the most important parts of the files may be found in Volumes 2-8.

<u>**ALL.ZIP** (175 MB of Free Disk Space Recommended)</u>

- /UMD-NREL Research Files - 23 directories, 11 files (3,275 kB)
  - /3honors - 1 file (2,635 kB)
  - /95tech - 1 file (4,075 kB)
  - /96sae - 1 file (4,935 kB)
  - /All Emtech Data in Text Format - 69 files (5,190 kB)
  - /Cycle - 6 files (4,665 kB)
  - /E6s_data - 2 files (16,375 kB)
  - /E6svalues - 3 files (245 kB)
  - /Erd_data - 17 files (3,025 kB)
  - /Inertia - 1 file (25 kB)
  - /Nrelpres - 1 file (4,535 kB)
  - /Plc_prog - 8 files (2,790 kB)
  - /Pre_test - 5 files (1,165 kB)
  - /Print - 4 files (23,905 kB)
  - /Progress - 6 files (195 kB)
  - /R14 - 1 file (1,340 kB)
  - /Report (early draft) – 2 files
  - /Steady - 1 directory, 2 files (450 kB)
    - /Original Emtech Data - 12 files (115 kB)
  - /Summary - 1 file (30 kB)
  - /Umd_cvt - 1 directory, 4 files (930 kB)
    - /Raw_data - 11 directories, 223 files (2,065 kB)
  - /Umd_emb - 4 directories, 3 files (320 kB)
    - /Belt_dat - 8 directories, 306 files (3,420 kB)
    - /Belt_xls - 9 files (425 kB)
    - /Em_dat - 5 directories, 342 files (3,505 kB)
    - /Em_xls - 4 files (245 kB)
  - /Umd_ice - 1 directory, 8 files (700 kB)
    - /Eng_data - 3 directories, 311 files (3,130 kB)
  - /Visio - 1 file (3,565 kB)
  - /Win_data - 13 files (23,480 kB)

LISTING OF FILES AND FILE REFERENCE GROUPS

REPORT.ZIP
> Final Report Excel Graphs.xls
> HEV Research Final Report.doc

Table 18. Final Report Reference Files

PRINT.ZIP
> 96NREL Address Symbols List, HP DeskJet 540.prn
> 96NREL Address Symbols List, HP LaserJet IIP plus.prn
> 96NREL Program Listing, HP DeskJet 540.prn
> 96NREL Program Listing, HP LaserJet IIP plus.prn

PLC_PROG.ZIP
> 96NREL Program Lookup Tables.xls
> Analog Voltage Component Calibrations.xls
> EM Assist Torque Control Analysis.xls
> EM Regenerative Torque Analysis, Manual Data Collection.xls
> Initial Battery Testing, Manual Data Collection.xls
> Programming Variables File.xls
> SOC Algorithm Testing, WinLINX Data Collection.xls
> Vehicle Speed Testing, 5-10-97.xls
CYCLE.ZIP
> 1373 cycle Discrete Data - KPH.xls
> Component Efficiency Analysis - SAE, HEV Procedure.xls
> HEV Spreadsheet Simulation for Optimization
> HWFET Discrete Data - KPH.xls
> Inertia Dyno Horsepower Setting.xls
> SAE-HEV Emissions Testing Discrete Values.xls
VISIO.ZIP
> 96nrel.vsd

Table 19. Allen-Bradley Programmable Logic Controller (PLC) Reference Files

LISTING OF FILES AND FILE REFERENCE GROUPS

UMD_CVT.ZIP
- > Cvt_anal.xls
- > Cvtgrafs.xls
- > Cvtmacro.xls
- > Transdat.xls
- **RAWDATA.ZIP**
  - > F2515301_PRN.xls
  - · ** s rr pp tt #.prn

INERTIA.ZIP
- > Ecvtin~1.xls

R14.ZIP
- > R14.doc

Table 20. ECVT Transmission Efficiency Testing Reference Files

E6VALUES.ZIP
- > E6s Program Values Analysis.xls
- > NREL_E85.E6M
- >NREL_M85.E6M

> E6S.EXE
> 96_FINAL.E6M

UMD_ICE.ZIP
- > 1996 Engine Data Analysis.xls
- > Emtech Bar Section Values.xls
- > Engine Data Analysis Macro.xls
- > Official Data Set Analysis.xls
- > Peter Data Set Analysis.xls
- > Repeated Data Set Analysis.xls
- > SAE Correction Factors.xls
- > Sequential Fuel Injector Timing Graph.xls
- **ENG_DATA.ZIP**
  - > O25_25_4_PRN.xls
  - > O25_25_4_TXT.xls
  - > ** d rr_tt_#.xxx

> PRE_ENG.XLS
3HONORS.ZIP
- > Chad’s Honors Paper.doc

Table 21. Internal Combustion Engine Efficiency Testing & Engine Management Reference Files

LISTING OF FILES AND FILE REFERENCE GROUPS

UMD_EMB.ZIP
- > Beltanal.xls
- > Em_anal.xls
- > Emuncty.xls
- **BELT_DAT.ZIP**
  - > S31_06_4_PRN.xls
  - > ** d rr_tt_#.prn
- **BELT_XLS.ZIP**
  - > Belt_.xls
  - > ** Belt_$.xls
- **EM_DAT.ZIP**
  - > A30_10_1_PRN.xls
  - > ** d rr_tt_#.prn
- **EM_XLS.ZIP**
  - > ** Em_$.xls

> EMBMACRO.XLS

Table 22. Electric Motor and Polychain Belt Efficiency Testing Reference Files

> 95SPECS.DOC
> 97SPECS.DOC
> 95TECH.DOC
> 96SAE.PPT
NRELPRES.ZIP
- > NREL Site Visit Presentation.ppt

PRE_TEST.ZIP
- > Battery Shipping Document, Testing Suggestions.doc
- > ECVT Testing Procedure.doc
- > Electric Motor & Belt Testing Uncertainty.doc
- > Engine Testing Uncertainty.doc
- > Transmission Testing Uncertainty.wp

> NICDBATT.XLS
> BATTERY DATA NOTES
> SAFT NI-CD 21-AHR BATTERY DATA.XLS
> US06.XLS

Table 23. Vehicle Background and Other Reports or Data Sent Reference Files

LISTING OF FILES AND FILE REFERENCE GROUPS

E6S_DATA.ZIP
> Emtech Data for All Tests, Combined Sections.xls
> First FTP-75 Emtech (Brief) Data Analysis.xls

ERD_DATA.ZIP
> Cumulative Emissions Data Summary.xls
> ERD Actual Vehicle Speed Comparison to Set Traces.xls
> LA-4 (E85-3) Speed Trace.xls
> ** Test Description, Speed Trace.txt

WIN_DATA.ZIP
> Charge Sustaining Tests, Dyno, LA-4, & HWFET, PLC Data.xls
> Charge Sustaining Tests, PLC Data, ANALYZED.xls
> First Cold Start FTP-75, PLC Data, ANALYZED.xls
> First Cold Start FTP-75, PLC Data.xls
> Last Cold Start FTP-75, PLC Data, ANALYZED.xls
> Last Cold Start FTP-75, PLC Data.xls
> Prelim Test, Hot 505, PLC Data, ANALYZED.xls
> Prelim Test, Hot 505, PLC Data.xls
> SAE-HEV, High SOC HWFET Cycles, PLC Data, ANALYZED.xls
> SAE-HEV, High SOC UDDS & HWFET Cycles, PLC Data.xls
> SAE-HEV, High SOC UDDS Cycles, PLC Data, ANALYZED.xls
> SAE-HEV, Low SOC UDDS Cycles, PLC Data, ANALYZED.xls
> SAE-HEV, Low SOC UDDS Cycles, PLC Data.xls

ALL EMTECH DATA IN TEXT FORMAT.ZIP
> ** Test Description, # Section.txt

STEADY.ZIP
> Combined & Analyzed Emtech Datalogging Data.xls
> Steady-state Chassis Dyno Testing Data & Analysis.xls

ORIGINAL EMTECH DATA.ZIP
> ** Vehicle Speed Description, Test #.txt

SUMMARY.ZIP
> New Cumulative Emissions Data Summary.xls

Table 24. Vehicle Fuel Economy and Emissions Testing Reference Files

DESCRIPTION OF ALL.ZIP FILES

Final Report Reference Files

REPORT.ZIP

Final Report Excel Graphs.xls - Contains all graphs, tables, and relevant data presented in the final report. All data in this file may in one way or another be found in other files but was copied here for quick reference and final report formatting without modifying the original reported data.

HEV Research Final Report.doc - Contains the draft version (9/97) of the report you are now reading.

Allen-Bradley Programmable Logic Controller (PLC) Reference Files

PRINT.ZIP

96NREL Address Symbols List, HP DeskJet 540.prn - A output file to be sent directly to an HP DeskJet 540 printer that contains all PLC program variable address references used in the 96NREL Program Listing, … .prn documentation. To print this file, use the MS-DOS command 'print', referring to 'help print' if user instructions are required.

96NREL Address Symbols List, HP LaserJet IIP plus.prn - An output file to be sent directly to an HP LaserJet IIP plus printer that is identical in content to 96NREL Address Symbols List, HP DeskJet 540.prn, but uses different printer formatting instructions.

96NREL Program Listing, HP DeskJet 540.prn - An output file to be sent directly to an HP DeskJet 540 printer that contains the PLC program used to control the vehicle. This file is presented in ladder logic format. Refer to the PLC programming section in this report for a brief ladder logic explanation. To print this file, use the MS-DOS command 'print', referring to 'help print' if user instructions are required.

96NREL Program Listing, HP LaserJet IIP plus.prn - An output file to be sent directly to an HP LaserJet IIP plus printer that is identical in content to 96NREL Program Listing, HP DeskJet 540.prn, but uses different printer formatting instructions.

PLC_PROG.ZIP

96NREL Program Lookup Tables.xls - Contains complete numerical data expansions and graphical representations of PLC program data referencing, i.e. lookup tables, and other important numerical calculations such as drive-by-wire engine/electric motor torque control.

Analog Voltage Component Calibrations.xls - Contains calibration data analysis for vehicle components which the PLC uses to observe and control vehicle operation.

EM Assist Torque Control Analysis.xls - Contains analysis of the electric motor and belt testing data to control the electric motor in the vehicle as a known assist torque input to the transmission.

EM Regenerative Torque Analysis, Manual Data Collection.xls - Contains data analysis of in-vehicle data collection during stationary charging to evaluate proper torque control of the electric motor in regenerative mode at the input to the transmission.

Initial Battery Testing, Manual Data Collection.xls - Contains battery state-of-charge (SOC) measurement data analysis to test the PLC program's SOC algorithm and lookup table SOC referencing.

Programming Variables File.xls - This is a mimic file of 96NREL Address Symbols, … .prn that uses Excel to group the variables into their respective files and variable types with slightly more detailed descriptions of their functions. Also contains the PLC input and output card addressing, a program subroutine listing, wire marker descriptions, and the PLC program debugging bit's use throughout the program.

SOC Algorithm Testing, WinLINX Data Collection.xls - Contains datalogging analysis of battery performance during stationary charging and electric only chassis dyno discharging to demonstrate the

PLC's SOC algorithm effectiveness. Real-time SOC data table references did not correct PLC algorithm values for SOC but were recorded for comparison.

Vehicle Speed Testing, 5-10-97.xls - Contains data collected while evaluating the vehicle speed signal and PLC program signal conditioning. Data was collected while operating the vehicle on a chassis dynamometer with a calibrated dyno analog speed output wired to the PLC.

CYCLE.ZIP

1373 cycle Discrete Data - KPH.xls - Contains a discrete data analysis of the Federal Urban Driving Schedule (FUDS) vehicle speed (kph) vs. time (sec) to show the percentage of time a vehicle is operated in discrete intervals of speed and acceleration rates, 10 kph and 0.30 m/s^2.

Component Efficiency Analysis.xls - SAE, HEV Procedure.xls - Contains an analysis of component efficiency optimization for the batteries, electric motor, engine, and transmission using the power requirements determined in HEV Spreadsheet Simulation for Optimization.xls and the SAE-HEV Test Procedure discrete time percentages found in SAE-HEV Emissions Testing Discrete Values.xls.

HWFET Discrete Data - KPH.xls - Contains a discrete data analysis of the Highway Fuel Economy Test (HWFET) vehicle speed (kph) vs. time (sec) to show the percentage of time a vehicle is operated in discrete intervals of speed and acceleration rates, 10 kph and 0.30 m/s^2.

HEV Spreadsheet Simulation for Optimization.xls - Uses tire rolling resistance data, vehicle weight, and vehicle aerodynamic properties to calculate vehicle power requirements at the discrete metric speed and acceleration values specified in SAE-HEV Emissions Testing Discrete Values.xls.

Inertia Dyno Horsepower Setting.xls - Contains indicated horsepower values displayed by the chassis dynamometer while fuel economy/emissions testing at Environmental Research & Development, Inc. This data was collected by hand and shows the graphical data analysis.

SAE-HEV Emissions Testing Discrete Values.xls - Combines the discrete data analysis results of 1373 cycle Discrete Data - KPH.xls and HWFET Discrete Data - KPH.xls into a lookup table matrix of time (sec) vs. vehicle speed (kph) vs. acceleration (m/s^2)

VISIO.ZIP

96_nrel.vsd - Describes the PLC ladder logic programming by using general flowcharting methods. This file was developed in Visio 2.0 and requires compatible software to view it.

ECVT Transmission Efficiency Testing Reference Files

UMD_CVT.ZIP

Cvt_anal.xls - Contains the data collection and analysis for the Electronic Continuously Variable Transmission (ECVT) efficiency testing. The efficiency data is grouped versus input speed (RPM), input torque (ft-lb), pulley ratio (input/output), and line pressure solenoid (On/Off).

Cvtgrafs.xls - Contains charts that graphically show the data analysis findings according to the Cvt_anal.xls efficiency data groupings and also in vehicle speed related groupings.

Cvtmacro.xls - Contains the custom Excel macros used in the transmission efficiency data analysis for both 6:1 and 9:1 output speed increasing gear ratios (9:1 gear ratio not used in actual testing). Uses Excel statistical formulas on the raw Daytronics data and organizes them according to their input speed, input torque, pulley ratio, and line pressure solenoid references.

Transdat.xls - Contains the uncertainty analysis report figures and data collection sheets used in the transmission dynamometer testing.

RAWDATA.ZIP

F2515301_PRN.xls - Contains an example of an actual ASCII text data file from the Daytronics DataPac in Excel format such that the data is in its correct comma delimited columns.

** s rr pp tt #.prn - Actual data files collected from the Daytronics DataPac in comma delimited, ASCII text format. Filename gives information relevant to all differentiating test conditions including solenoid switch position (s, O[N] or Of [F]), input speed (rr, RPM/100), pulley ratio (pp, ratio x10), test session (tt [0 to 11]), and a number indicating the file's order in repeated data points (#).

INERTIA.ZIP

Ecvtin~1.xls - Contains the data analysis of estimated internal transmission component mass inertia.

R14.ZIP

R14.doc - The thesis report prepared by our German exchange student, Rainer Vogel, describing the ECVT transmission testing apparatus's design, construction, and preliminary testing.

Emtech E6s Engine Management System Reference Files

E6VALUES.ZIP

E6s Program Values Analysis.xls - Contains critical fuel injection parameters programmed in the Emtech Engine Management System (EMS) for ethanol (E85) and methanol (M85) engine operation. Indicates program calibration values of the fuel injector on-time and spark advance based upon coolant temperature, manifold air pressure (MAP), engine speed, and cold start cranking.

NREL_E85.E6M - Emtech EMS calibration file used by E6s.exe to store parameters for ethanol (E85) engine operation in the vehicle.

NREL_M85.E6M - Emtech EMS calibration file used by E6s.exe to store parameters for methanol (M85).

E6S.EXE - Emtech EMS calibration software for fuel injection programming. This software is designed to run in an MS-DOS environment.

96_FINAL.E6M - Emtech EMS calibration file saved after engine dynamometer testing with M85 fuel.

Internal Combustion Engine Efficiency Testing Reference Files

UMD_ICE.ZIP

1996 Engine Data Analysis.xls - Contains the combined data collection and analysis for the engine efficiency testing sessions of Official, Peter, and Repeated. The efficiency data is grouped versus engine speed (RPM) and output torque (ft-lb). Data was combined from Official, Peter, and Repeated data sessions for the best operating points of the engine as testing calibrations were completed.

Emtech Bar Section Values.xls - Contains calibration intervals (bars) used in the Emtech programming software for intake manifold air pressure (MAP, differential kPa or in-Hg) and coolant temperature (degrees Celsius or Fahrenheit).

Engine Data Analysis Macro.xls - Contains the custom Excel macros used in the engine efficiency data analysis. Uses Excel statistical formulas on the raw Daytronic DataPac and Emtech datalogging data and organizes them according to their RPM and torque references.

Official Data Set Analysis.xls - Data collection and analysis for the first engine efficiency testing session. The efficiency data is grouped versus engine speed (RPM) and output torque (ft-lb). The engine's full steady state operating range was tested after general spark advance optimization was completed.

Peter Data Set Analysis.xls - Data collection and analysis for the third engine efficiency testing session. The efficiency data is grouped versus engine speed (RPM) and output torque (ft-lb). This testing session was completed to improve comparatively low efficiency areas due to non-optimized spark advance calibrations in the 2,500 RPM engine speed range.

Repeated Data Set Analysis.xls - Data collection and analysis for the second engine efficiency testing session. The efficiency data is grouped versus engine speed (RPM) and output torque (ft-lb). This testing session was completed to have comparison data for Official Data Set Analysis.xls. Limited spark advance modifications were made.

SAE Correction Factors.xls - Contains correction factors used to evaluate engine performance at standard pressure (760 mm Hg), temperature (25° Celsius), and relative humidity (0%) as recommended by the Society of Automotive Engineers (also contains corrections for other standard operating conditions).

Sequential Fuel Injector Timing Graph.xls - Contains engine valve timing and lift data to demonstrate graphically findings of hydrocarbon emission reductions vs. sequential fuel injector timing relative to the intake valve opening.

ENG_DATA.ZIP

O25_25_4_PRN.xls - Contains an example of an actual ASCII text data file from the Daytronics DataPac in Excel format such that the data is in its correct comma delimited columns.

O25_25_4_TXT.xls - Contains an example of an actual ASCII text data file from the Emtech datalogging calibration software in Excel format such that the data is in its correct fixed width columns. Each *.txt file was converted from an Emtech *.hdl datalog storage file sent to a printer using E6s.exe print options and intercepted by ASCII text print capture software.

** d rr_tt_#.xxx - Actual data files collected from the Daytronics DataPac in ASCII text format. Filename indicates the data test session (d, i.e. ‘O’ for Official), engine speed (rr, RPM/100), output torque (tt, ft-lb), and a number indicating the file’s order in repeated data points (#).

PRE_ENG.XLS - Contains some engine performance data obtained prior to the start of this contract. This data was sent to give an indication of the new testing data that could be expected.

3HONORS.ZIP

Chad’s Honors Paper.doc - A senior undergraduate honors thesis prepared by Chad Reithmeier giving qualitative data analysis of the cold-start idle, tailpipe performance of three engine emission components, both independently and in various combinations. Emission components included in this study were an Electrically Heated Catalyst (EHC), a Phase Change Material (PCM) Heat Battery (HB), and an electric Exhaust Air Pump (EAP)

Electric Motor and Polychain Belt Efficiency Testing Reference Files

UMD_EMB.ZIP

Beltanal.xls - Contains the data analysis for the combined electric motor/belt system efficiency testing sessions ‘Q’ through ‘V’. The empirical total system efficiency and computed belt efficiency data is grouped versus dyno speed (RPM) and dyno torque (ft-lb). Data was collected initially, i.e. the first two test groups ‘O’ and ‘P’, such that the dyno speed matched the electric motor speed of previous testing collection points examined in Em_anal.xls. In subsequent testing sessions, data was collected such that the computed electric motor (EM) speed, accounting for the pulley gearing of 1.2:1, identically matched the EM speed intervals chosen for the EM efficiency testing in Em_anal.xls.

Em_anal.xls - Contains the combined data analysis for the electric motor efficiency testing sessions. The efficiency data is grouped versus electric motor speed (RPM) and output torque (ft-lb). Data was collected from test sessions ‘A’ through ‘D’, weighted equally, averaged, and evaluated for statistical deviations.

Emuncty.xls - Contains data used in determining final efficiency uncertainty estimates for the electric motor efficiency testing and belt efficiency testing. Examples of data sheets used in testing are also included in this file.

BELT_DAT.ZIP

S31_06_4_PRN.xls - Contains an example of an actual ASCII text data file from the Daytronics DataPac in Excel format such that the data is in its correct comma delimited columns.

** d rr_tt_#.prn - Actual data files collected from the Daytronics DataPac in comma delimited, ASCII text format. Filename indicates data test session (d, alphabetical order from 'O' to 'V'), electric motor speed (rr, RPM/100), output torque (tt, ft-lb), and a number indicating the file's order in repeated data points (#).

BELT_XLS.ZIP

Belt_.xls - A blank belt efficiency data analysis file containing all necessary worksheets used in taking data from an ASCII text file and evaluating it using Embmacro.xls.

** Belt_$.xls - Eight files ($ indicates test sessions 'O' through 'V'), one for each belt efficiency testing session, containing data collection and analysis of the electric motor/belt system efficiency measurements. The efficiency data is grouped versus dyno input speed (RPM) and input torque (ft-lb). Various belt tensions were tested in different sessions.

EM_DAT.ZIP

A30_10_1_PRN.xls - Contains an example of an actual ASCII text data file from the Daytronics DataPac in Excel format such that the data is in its correct comma delimited columns.

** d rr_tt_#.prn - Actual data files collected from the Daytronics DataPac comma delimited, ASCII text format. Filename indicates data test session (d, alphabetical order from 'A' to 'D'), dyno speed (rr, RPM/100), dyno torque (tt, ft-lb), and a number indicating the file's order in repeated data points (#).

EM_XLS.ZIP

** Em_$.xls - Four files ($ indicates test sessions 'A' through 'D'), one file for each test session, containing data collection and analysis of the electric motor efficiency measurements. Test points were repeated four times to examine measurement uncertainty and repeatability. The efficiency data is grouped vs. dyno input speed (RPM) and input torque (ft-lb).

EMBMACRO.XLS - Contains the custom Excel macros used for the electric motor efficiency and belt system efficiency data analyses. Uses Excel statistical formulas on the raw Daytronic data and organizes them according to their RPM and torque references.

Vehicle Background and Other Reports or Data Sent Reference Files

95SPECS.DOC - A brief two page document which summarizes the vehicle performance, components, and operation. Compiled after 1995 design changes for presentation and display reference materials.

97SPECS.DOC - A modified version of 95spec.doc which includes changes made to the vehicle during this research period, but does not incorporate the latest performance data due to its FTP transfer date.

95TECH.DOC - The University of Maryland team technical report submitted to the 1995 HEV Challenge organizers. Published by SAE in a collection of HEV Challenge technical reports from all participating teams.

96SAE.PPT - The presentation given by Fred Householder at the 1996 SAE International Congress and Exposition entitled The Influence of Component Efficiency upon Control Strategy Optimization.

NRELPRES.ZIP

NREL Site Visit Presentation.ppt - The presentation given to Warren Salt during his visit to the University of Maryland as our contract monitor. Covers major topic areas such as transmission efficiency testing results, engine efficiency testing results, electric motor efficiency and belt efficiency testing results, emission component testing results, and vehicle control programming progress.

PRE_TEST.ZIP

Battery Shipping Document, Testing Suggestions.doc - The document sent in conjunction with 10 nickel-cadmium cells to NREL in October 1996. Covers vehicle battery pack properties, typical vehicle use, suggested testing procedures, and preferred testing results.

ECVT Testing Procedure.doc - A brief one page explanation of the transmission efficiency testing procedure. Describes how typical data sets were accumulated.

Electric Motor & Belt Testing Uncertainty.doc - Written prior to actual testing, this file discusses the measurement, analysis, and anticipated typical uncertainty estimates for the electric motor efficiency and belt efficiency testing in order to assure appropriate experiment measurements were being taken.

Engine Testing Uncertainty.doc - Written prior to actual testing, this file discusses the measurement, analysis, and anticipated typical uncertainty estimates for the engine efficiency testing in order to assure appropriate experiment measurements were being taken.

Transmission Testing Uncertainty.wp - Written prior to actual testing, this file discusses the measurement, analysis, and anticipated typical uncertainty estimates for the transmission efficiency testing in order to assure appropriate experiment measurements were being taken..

NICDBATT.XLS - The accompanying Excel file to Battery Shipping Document, Testing Suggestions.doc which contains manufacturer data and analysis to assist the development of a testing procedure.

US06.XLS - Contains vehicle speed (mph) vs. time (sec) for the new high speed, high acceleration driving schedule being examined by the Environmental Protection Agency (EPA) as an additional part of vehicle certification.

Vehicle Fuel Economy and Emissions Testing Reference Files

E6S_DATA.ZIP

Emtech Data for All Tests, Combined Sections.xls - Contains all text data stored by the Emtech EMS during fuel economy and emissions testing. This data is organized in worksheets according to its reference driving test. All original data may be found in All Emtech Data in Text Format.zip.

First FTP-75 Emtech (Brief) Data Analysis.xls - Examines one driving test's Emtech EMS data to show the data's relevance in analyzing the vehicle's performance during the fuel economy testing.

ERD_DATA.ZIP

Cumulative Emissions Data Summary.xls - First version of the combined emissions and fuel economy test data from Environmental Research & Development, Inc. (ERD) showing gross and net values for hydrocarbons, carbon monoxide, carbon dioxide, and nitrous oxides. Alcohol fuel energy content values were yet available, thus the vehicle fuel economy is given assuming gasoline fuel. The second version of this file is provided in Summary.zip.

ERD Actual Vehicle Speed Comparison to Set Traces.xls - Examines two data sets of actual vehicle speed during a test to the procedure specified vehicle speed. Shows improved driveability through the decrease of speed differences and the extent of vehicle repeatability in following the speed trace.

** Test Description, Speed Trace.txt - These files contain the actual vehicle speed (mph) vs. time (tenths of a second) for various fuel economy/emissions tests. Data recorded by ERD testing equipment.

WIN_DATA.ZIP

Charge Sustaining Tests, Dyno, LA-4 & HWFET, PLC Data.xls - Unmodified data recorded by PLC WinLINX software of dyno testing performed at ERD to observe SOC fluctuations at expected engine torque control settings. Emissions and fuel economy data was not recorded for this R&D tests.

Charge Sustaining Tests, PLC Data, ANALYZED.xls - Analyzed and graphed data of the tests described above. Procedure specified speed traces were imposed on the data to serve as a known reference. A full graphical analysis was not performed on this data because of its R&D purpose.

First Cold Start FTP-75, PLC Data, ANALYZED.xls - Analyzed and graphed data of the first FTP-75 fuel economy/emissions test performed on the vehicle. Bags 1 & 2 are analyzed together as a UDDS schedule, bag 3 separately as a 505 schedule. Six multiple line graphs depict nearly all critical characterization variables for each data set as a function of time, also plotting vehicle speed to be used as a known reference.

First Cold Start FTP-75, PLC Data.xls - Unmodified data recorded by PLC WinLINX software of the first FTP-75 fuel economy/emissions test performed on the vehicle mentioned above.

Last Cold Start FTP-75, PLC Data, ANALYZED.xls - Analyzed and graphed data of the final FTP-75 fuel economy/emissions test performed on the vehicle. Full graphical data analysis was performed.

Last Cold Start FTP-75, PLC Data.xls - Unmodified data recorded by PLC WinLINX software of the final FTP-75 fuel economy/emissions test performed on the vehicle.

Prelim Test, Hot 505, PLC Data, ANALYZED.xls - Analyzed and graphed data of the first attempted fuel economy/emissions test performed on the vehicle. Improper engine operation required that the test be cut short of completion. Therefore, a full graphical analysis was not performed on this data.

Prelim Test, Hot 505, PLC Data.xls - - Unmodified data recorded by PLC WinLINX software of the incomplete first fuel economy/emissions test described above.

SAE-HEV, High SOC HWFET Cycles, PLC Data, ANALYZED.xls - Analyzed and graphed data of four Highway Fuel Economy Tests (HWFET). A full HWFET prep test was completed first, followed immediately by a fuel economy/emissions recorded HWFET. After a 10 minute hot soak, two more HWFET's were driven, the second immediately following the other. Four multiple line graphs depict nearly all critical characterization variables for each data set as a function of time, also plotting vehicle speed to be used as a known reference.

SAE-HEV, High SOC UDDS & HWFET Cycles, PLC Data.xls - Unmodified data recorded by PLC WinLINX software of a pseudo Day 4 of the SAE-HEV Test Procedure Draft, J1711. Includes data of two UDDS fuel economy/emissions tests followed by four HWFET fuel economy/emissions tests (one serving as a prep). The vehicle's battery State-of-Charge is started at " SOC+ " in reference to the procedure's UDDS testing of Day 2.

SAE-HEV, High SOC UDDS Cycles, PLC Data, ANALYZED.xls - Analyzed and graphed data of two UDDS fuel economy/emissions tests as described above. A full graphical analysis was performed on the data to give six multiple line graphs depicts nearly all vehicle characterization variables.

SAE-HEV, Low SOC UDDS Cycles, PLC Data, ANALYZED.xls - Analyzed and graphed data of two UDDS fuel economy/emissions tests resembling a pseudo Day 5 of the SAE-HEV Test Procedure Draft, J1711. For these tests, an " SOC- " was chosen in reference to the procedure's UDDS testing of Day 2. A full graphical analysis was performed on the data.

SAE-HEV, Low SOC UDDS Cycles, PLC Data.xls - Unmodified data recorded by PLC WinLINX software of the pseudo Day 5 of the SAE-HEV Test Procedure mentioned above.

ALL EMTECH DATA IN TEXT FORMAT.ZIP

** Test Description, # Section.txt - Contains original software captured, ASCII print text, Emtech EMS data which is stored in sections of 100 printed pages or less and were eventually combined by testing sessions in Emtech Data for All Tests, Combined Sections.xls.

STEADY.ZIP

Combined & Analyzed Emtech Datalogging Data.xls - Contains Emtech EMS fuel injection time, RPM, and MAP data relevant to the steady state power dyno testing performed at the Univ. of Maryland FutureCar lab. This data was analyzed to provide a fuel energy usage rate and thus enable calculations of total drivetrain efficiency.

Steady-state Chassis Dyno Testing Data & Analysis.xls - Combines PLC WinLINX software data and analyzed Emtech EMS data from Combined & Analyzed Emtech Datalogging Data.xls to determine total and partial drivetrain efficiency at 20, 30, and 50 mph, various wheel loads at each speed to represent cruising, acceleration, and deceleration conditions.

ORIGINAL EMTECH DATA.ZIP

** Vehicle Speed Description, Test #.txt - Contains original Emtech EMS data used in Combined & Analyzed Emtech Datalogging Data.xls and identified to its data set by the filename.

SUMMARY.ZIP

New Cumulative Emissions Data Summary.xls - Second version of Cumulative Emissions Data Summary.xls which includes alcohol fuel energy content to give gasoline equivalent fuel economy results along with all gross and net ERD emission measurements.